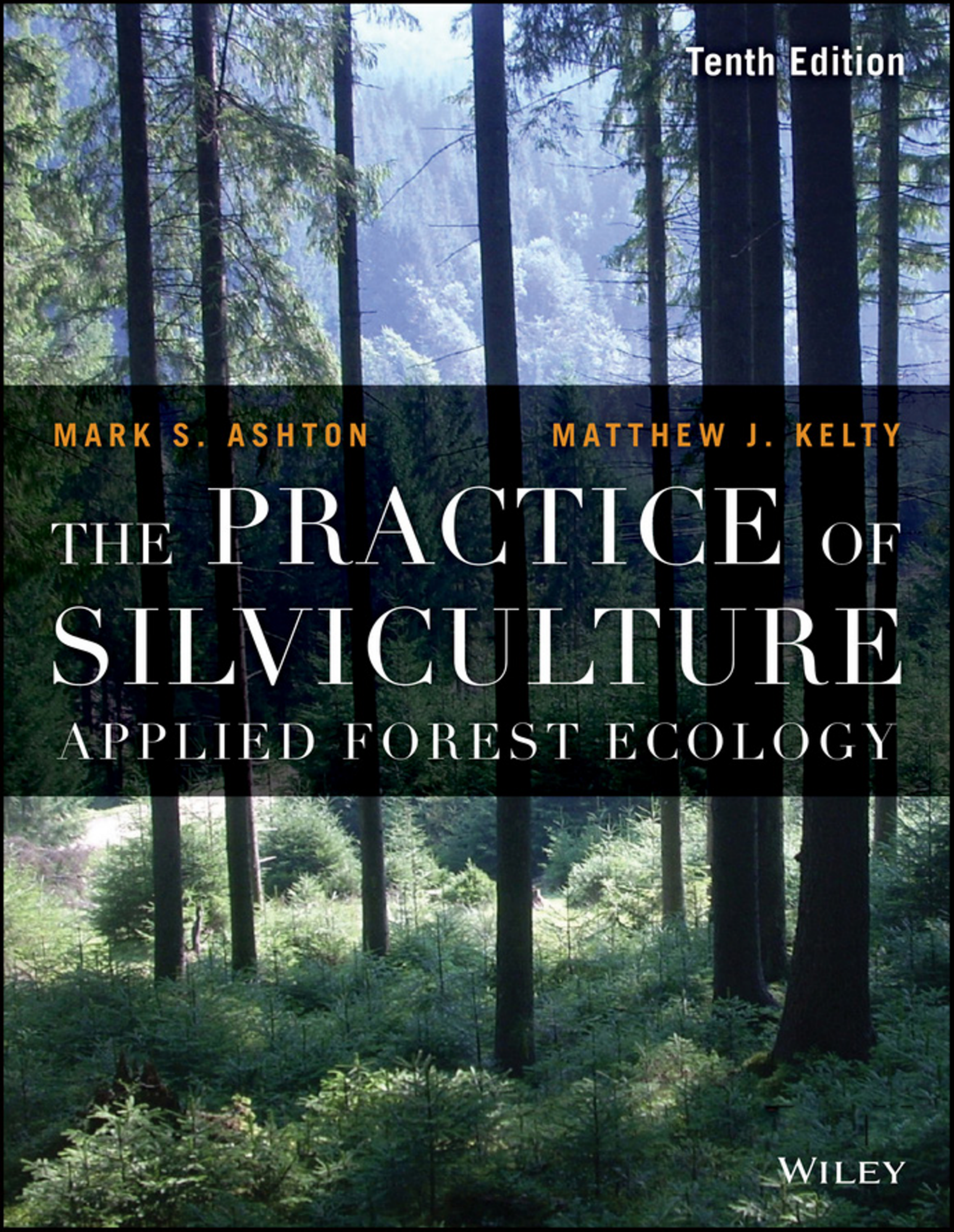


Tenth Edition

MARK S. ASHTON

MATTHEW J. KELTY

THE PRACTICE OF SILVICULTURE

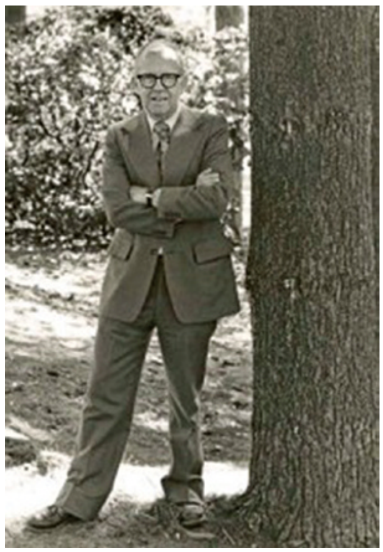
APPLIED FOREST ECOLOGY

WILEY

The Practice of Silviculture

Dedication

DAVID MARTYN SMITH
March 10, 1921–March 7, 2009



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David M. Smith, longtime Professor of Silviculture at Yale University, was our mentor and our friend. We dedicate this 10th edition of *The Practice of Silviculture* to his memory, in thanks for all he gave to us.

Dave was born in Texas and raised in Rhode Island. After graduation from the University of Rhode Island, he served as a meteorologist for the US Army Air Force during World War II. He earned his masters and doctorate degrees from Yale University under the guidance of Professor Harold Lutz. Dave quickly became a faculty member in the School of Forestry and Environmental Studies at Yale. One of his most notable contributions involved helping to found the sub-discipline of silviculture known as *forest stand dynamics*, which uses stand reconstruction to evaluate the past and to project the future of forest growth. During his years at Yale, Dave served as the Director of School Forests and as the Morris K. Jesup Professor of Silviculture. His wit and wisdom are fondly remembered, as are the many lessons taught in the classroom and in the field. Dave educated a legion of professionals who have had a lasting impact on forests throughout the world.

David Smith worked with Ralph C. Hawley as co-author of the 6th edition of this book, and then went on to author the 7th and 8th editions alone. He was lead author on the 9th edition, working with three of his former students. In his field trips and teaching, Dave showed his students how a practical knowledge of botany, ecology, and geology could allow a forester to look at a stand of trees, pick out clues, and make deductions about the forces shaping the forest. His skills in this area led some students to dub him "Sherlock Holmes of the forest." We are ever grateful for his wisdom and guidance.

Mark S. Ashton
Matthew J. Kelty

The Practice of Silviculture

Applied Forest Ecology

Tenth Edition

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Preface

The late Ralph C. Hawley, one of the pioneers of American forestry, wrote the first edition of this book in 1921. He based it on knowledge imported from Europe and on what he, and a few hundred foresters, had learned by managing the limited tracts of forest on which true long-term forestry was being practiced. At the time, American society regarded forests only as a source of timber, and the book focused on timber production silviculture that would be financially sound in the long run. Professor Hawley went on to revise the book four times. David M. Smith became a co-author on the 6th edition, published in 1956. Emphasis was placed on presenting the scientific basis for silvicultural practice. Professor Smith wrote and edited two more editions as sole author. In the 9th edition, Professor Smith brought on three colleagues, all of whom were his past students: Bruce C. Larson, Matthew J. Kelty, and Mark S. Ashton. His intent was to carry on the tradition of the text in the same manner in which Professor Hawley had worked with him. In the 9th edition, published in 1997, the phrase *Applied Forest Ecology* was added to the title. The basic purpose was to call attention to the fact that foresters should design forests based on sound ecological theory. This applied ecology is concerned with managing the interactions among organisms and their environment, regardless of the degree to which the forests are managed or devoid of human influence.

This 10th edition is a significant revision of the 1997 text. The contents have been completely restructured to further emphasize the ecological basis for silviculture, as well as to expand the relevance of silviculture to a range of forest and tree-related resource management issues. In this edition there are six parts: (1) an introduction and history of silviculture, (2) a summary of the ecological foundations for silvicultural practice, (3) methods of regeneration, both natural and artificial, (4) post-establishment (intermediate) treatments, (5) silvicultural considerations for forest management, and (6) examples of applications for different land ownerships and uses. The previous edition began with intermediate treatments; this book starts with concepts and treatments for regeneration, then progresses to intermediate treatments. The text ends with a new and more elaborate section on applications of silviculture to different resource issues: industry and industrial management, public lands and ecosystem management, restoration and forest health, watershed management, wildlife habitat, agroforestry, urban environments, and climate mitigation.

The 10th edition has been expanded and largely rewritten with clearer language and explanations, updated references, and new photographs, tables, and figures. Boxed inserts have been added to provide greater detail on particular silvicultural treatments or examples of their use. Each chapter strives to provide regional examples for the southern, northeastern and western United States. The glossary contains words and phrases which are highlighted in the text using bold color font. Words in black bold font are for emphasis only.

The book still has a strong North American focus, but contains more examples from across the world to provide a more global perspective of silvicultural use for the North American forester or student. This may be the most expansive book on silviculture yet, and covers a wide range of topics and resource issues that are currently faced by the forester or resource professional. It does not lose its strength in explaining the principles for silvicultural treatments.

Work on this 10th edition began over 10 years ago. The long process has involved many people acknowledged elsewhere in these initial pages. It is hoped that this effort will be well received and appreciated by the forestry community. We thank our families for their patience and the time we have been allowed in preparing this book.

Mark S. Ashton, Morris K. Jesup Chair of Silviculture and Forest Ecology, Yale University
Matthew J. Kelty, Professor Emeritus, University of Massachusetts Amherst

Acknowledgements

There are many individuals who have helped in a variety of ways with this book. We would not have been able to do this book without the fundamental and ever present help of D'Ann Kelty. We would also like to thank our close colleague Bruce Larson at the University of British Columbia, who helped with initial writing of Chapter 24 and provided many helpful suggestions and edits throughout the text as this book was being developed. Each chapter was reviewed by students from Mark Ashton's silviculture class at Yale University, and by many of our colleagues at universities in North America. In particular we would like to acknowledge the silviculture instructors and researchers who reviewed multiple chapters of the book and provided many, many helpful comments. In alphabetical order they are: Heidi Asbjornsen (University of New Hampshire), John Bailey (Oregon State University), Graeme Berlyn (Yale University), Craig Brodersen (Yale University), Wayne Clutterbuck (University of Tennessee), Phil Comeau (University of Alberta), Kristofer Covey (Yale University), Anthony D'Amato (University of Vermont), Tom Dean (Louisiana State University), Mark Ducey (University of New Hampshire), Marlyse Duguid (Yale University), David Ellum (Warren Wilson College), Andrew Ezell (Mississippi State University), Michael Ferrucci (InterForest LLC), Alex Finkral (The Forestland Group), Thomas Fox (Virginia Polytechnic Institute and State University), Brent Frey (Mississippi State University), John Goodburn (University of Montana), John Groninger (Southern Illinois University), James Guildin (US Forest Service), Jefferson Hall (Smithsonian Tropical Research Institution), John Hodges (deceased, formerly of Mississippi State University), Jennifer Hoyle (Yale University), Steven Jack (Jones Ecological Center), Thomas James (Hama Hama Forest Resources), Eric Jokela (University of Florida), Shibu Jose (University of Missouri), Kathleen Kavanagh (Texas A & M), David Kittredge (University of Massachusetts), Karen Kuerrs (University of the South), David Larsen (University of Missouri), Xuhui Lee (Yale University), Victor Lieffers (University of Alberta), Brian Lockhart (US Forest Service), James Long (Utah State University), Doug Maguire (Oregon State University), Florencia Montagnini (Yale University), David Moorehead (University of Georgia), Colleen Murphy-Dunning (Urban Resources Initiative, Yale University), Linda Nagel (Colorado State University), Kevin O'Hara (University of California, Berkeley), Klaus Puettmann (Oregon State University), James Saiers (Yale University), Mike Saunder (Purdue), Oswald Schmitz (Yale University), Robert Seymour (University of Maine), David Skelly (Yale University), Steven Tesch (Oregon State University), Geoff Wang (Clemson University), Kristen Waring (Northern Arizona University), and Eric Zenner (Pennsylvania State University).

A core group of Yale University graduate students reviewed and provided edits on the chapters. They include: Karin Bucht, Vihn Lang, Anthony Mecum, Serena Liam, Nicholas Olson, Frances Sawyer, Kristina Solheim, and Sabrina Szeto. We would like to thank them most sincerely for their efforts. They were very important in making sure the book read well, and was understandable, for the main audience and readership it is intended for. We also thank Julius Pasay for preparing the information for several of the boxes in Chapters 1 and 2.

Finally we would like to thank Yale University and the US Forest Service and many other organizations and individuals who have been credited with photographs and figures within the book.

Part 1

Introduction to Silviculture

A history of silviculture and the philosophical approach taken in this book.

1

The History and Philosophy of Silviculture

Introduction

There are three parts to this chapter that describe silviculture as an evolving sub-discipline of applied ecology and its contribution to the well-being of society. The three parts include: (1) history, (2) philosophy, and (3) the literature and sub-disciplines of research relevant to current resource issues. The first part summarizes the origins and evolution of silviculture as a part of an ancient indigenous agricultural practice used by many peoples for production of food and shelter in combination. Silviculture was originally the forest part of swidden systems where forest patches were cleared for agricultural use for a period of years to provide food, before being left fallow and allowed to grow back to trees, and secondary forest that was harvested for timber, fiber, fruits, and medicinals. With the development of permanent agricultural and pastoral fields, silvicultural systems followed suit and forests and woodlands were managed separately from agriculture. There is then a discussion of silviculture's systematic evolution as a science in response to the degeneration and degradation of forest lands associated with the industrialization of economies in central Europe, then in North America, and subsequently elsewhere. A synopsis of silviculture's roots to reforestation and restoration in Germany, British India, and the United States follows. Finally there is a discussion of silviculture as it is practiced at present.

The second part comprises a discussion of the different philosophical approaches of silviculture. It first describes silviculture as an ecological technology. It shows that silviculture has a relationship with the social sciences and contributes to the management discipline of forests and woodlands. It describes how silviculture should be used as part of a long-term economic view for the betterment and sustainability of social values obtained from trees. It then discusses the variations in the intensity of practice in relation to circumstance. This part of the chapter concludes with a philosophical perspective of how silviculture should be applied to forests.

The third part comprises a synthesis of the silvicultural literature as a body of scientific knowledge. It uses the literature to discuss modern day developments in silvicultural research as a sub-discipline of ecology, and then relates this body of research to today's resource issues.

Silviculture, its Origin and Development as an Applied Ecology

Silviculture is the oldest application of the science of ecology and is a field that was recognized before the term *ecology* was coined (Toumey, 1928). Many of the ways of developing forest stands rest heavily on cuttings that alter or modify the stand environment in order to regulate the growth of remaining vegetation. The reliance on ecological knowledge in silviculture is therefore all the better for not simply resting on philosophical principle. The economic returns from forestry are usually not great enough to protect forests from all the shifts and changes of nature. Therefore, silviculture is usually far more the imitation of the natural processes of forest growth and development, than of completely substituting a new stand for them.

Silviculture as a Preindustrial Construct

Silviculture, as a practice of cultivating and growing vegetation within forests and woodlands, has a much longer history of development and learning over thousands of years than its more recent transformation into a science. The most ancient form of silviculture was, and still is in the more remote forests of the world, a part of what is called **swidden agriculture**. It is a temporary intensive cultivation of a patch of cleared forest for food crops, which is then either abruptly or more slowly relinquished back to forest through succession. It is widely practiced in the more remote forest regions of the world and can be a very sustainable form of agri-silviculture.

Such systems have different lengths of successional development before returning back for cultivation. They are largely dependent upon the soil's inherent capacity to become fertile again. After cultivation of arable crops is stopped, many swidden systems incorporate tree

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

plantings and intentional natural regeneration methods that are then followed up with the tending and harvesting of tree crops. Trees that provide fruits, medicinals, and building materials can be harvested with the growth of the new forest into the future until the next cycle of forest clearance and cultivation (Box 1.1). People who practiced swidden agriculture knew exactly where, when, and what tree species to cultivate within a swidden. Many swidden systems can be regarded as very sophisticated, much more so than the credit given them by western science and the modern day practice of agriculture and forestry.

In particular regions of the world, agriculture developed into a permanent practice of cultivation allowing people to settle. These regions can be considered the birth places of modern agriculture and of the origins of civilization (Fig. 1.1). In addition to permanent agriculture came silvicultural practice to produce the goods and services desired from these agricultural systems. Such systems resulted in complex land-use practices with a mixture of intensive to non-intensive treatments reflecting the inherent productivity gradient across a landscape (Box 1.2).

Across most of Europe and the British Isles up to the 18th century, the monarchy, the church, or the nobility held the land rights to hunt and to extract large timbers for shipbuilding and construction. Peasant and tenant

Box 1.1 Examples of preindustrial silviculture.

Swidden Cultivation System of the Yanomami in Brazil

The Yanomami Native Americans are one of the largest tribes in Latin America, straddling the borderlands of northern Brazil and southern Venezuela. The combined Yanomami territories of Brazil, comprising 23.7 million acres (9.6 million ha), and Venezuela, comprising 20.3 million acres (8.2 million ha), form the largest indigenous lands in the world (Chagnon and Gross, 1973). The lands are under threat from goldminers, cattle ranchers, and poor national government enforcement. The Yanomami live in relatively large communal houses called yanos. Men hunt and fish for game, providing about 10% of the food; women farm, providing about 80%. Only about 4 hours of work per day is necessary to maintain their way of life. Villages periodically move within the territory about every 30 years to accommodate the shifting agricultural systems. Large gardens are cleared by the men from primary forest (old-growth) and crops (cassava, sweet potatoes, plantains, beans, corn, squash) are cultivated by the women for only 2–3 years because the soils are so infertile (Fig. 1). New gardens are then created in another patch of primary forest. Old gardens are used for hunting animals that like early successional habitat, harvesting insect grubs feeding upon young growth, and harvesting fruit, medicinals, and vines for cordage and basketry (Nilsson and Fearnside, 2011). It usually takes no longer than 2 hours walk to get to a garden from the village. Several gardens are worked at the same time. In other areas, the Yanomami have old groves of fruit

Box 1.1 Figure 1 An aerial view of swidden cultivation in the Amazon comprising a patchwork of current and abandoned fields. *Source:* R. Butler, 2008. Reproduced with permission from Rhett Butler/mongabay.com.

Box 1.1 (Continued)

trees planted and then protected from years ago. The total number of plant species used by the Yanomami is well over 500 and cater to every necessity of life ranging from toothpicks, to foods, to medicines, to fish poisons. Hunting for different purposes is carefully zoned across the forest for different kinds of game and for hunting at different seasons and even times of day. Other zones are restricted as game preserves. All of this means there is an extensive trail network for the different hunting and gardening practices.

Cultivation Systems of Native Americans in Eastern North American Oak Forests

Indigenous peoples of North America strongly influenced the landscape vegetation of the eastern oak forests of the United States. They did this by cultivating crops. However they also manipulated tree density and species composition to increase mast and game populations, to encourage easy woodland travel, and to reduce pests and diseases. Eastern tribes cultivated maize, beans, squash, and tobacco, often on a large scale, and sited these clearings on fertile soils most suitable for agriculture, usually in large river flood plains. Early explorers reported extensive areas of cultivation. In 1616, Smith remarked that the Massachusetts coast "shewes you all along large cornfields" and "many Iles all planted with corne" (Day, 1953). In New England, cultivation shifted after soil exhaustion and more forest had to be cleared for new fields. This kind of cultivation created a patchwork of successional ages and structures (Cronon, 1983). In addition to intensively managing agricultural fields, Native Americans managed forests to create open savannah woodlands with grassy understories and widely spaced trees. These woodlands were primarily composed of fire-adapted, masting species such as oaks, chestnuts, and hickories. In 1525, Giovanni da Verrazzano traveled 15–18 miles inland from Narragansett Bay, Rhode Island and observed open plains, completely free of trees, extending miles, as well as woodlands that "might well be traversed by an army ever so numerous." (Verrazzano, 1825 in Day, 1953 p. 334). Other early explorers echoed such reports and also noted the large and numerous fires, which were ignited annually or twice a year in the spring and fall. These fire-maintained savannahs had several purposes, chief among them being the provision of food. Frequent fires favored nut-producing hardwoods, such as oaks, particularly the sweet acorn-bearing white oaks, chestnuts, hickories, walnuts, and butternuts, and maintained them in open conditions, maximizing sun exposure and thus mast volumes. Nut collection was also facilitated by the open understory. The growth of fruit-bearing understory plants such as blueberries, raspberries, strawberries, and hazels was also encouraged. Not only did these savannahs feed humans directly but they also supported abundant game populations (Abrams and Nowacki, 2008). Denton (1670) reported "stately Oaks" with "broad-branched-tops" and "grass as high as a man's middle, that serves for no other end except to maintain the Elk and Deer, … then to be burnt every spring to make way for new" forage (Day, 1953). Just as frequent fires increased game populations, they reduced populations of pests such as rodents, ticks, and fleas (Williams, 2005). In fact, the Narragansetts listed the "destroying of vermin" as a reason for burning in their discussions with Roger Williams in 1643 (Day, 1953).

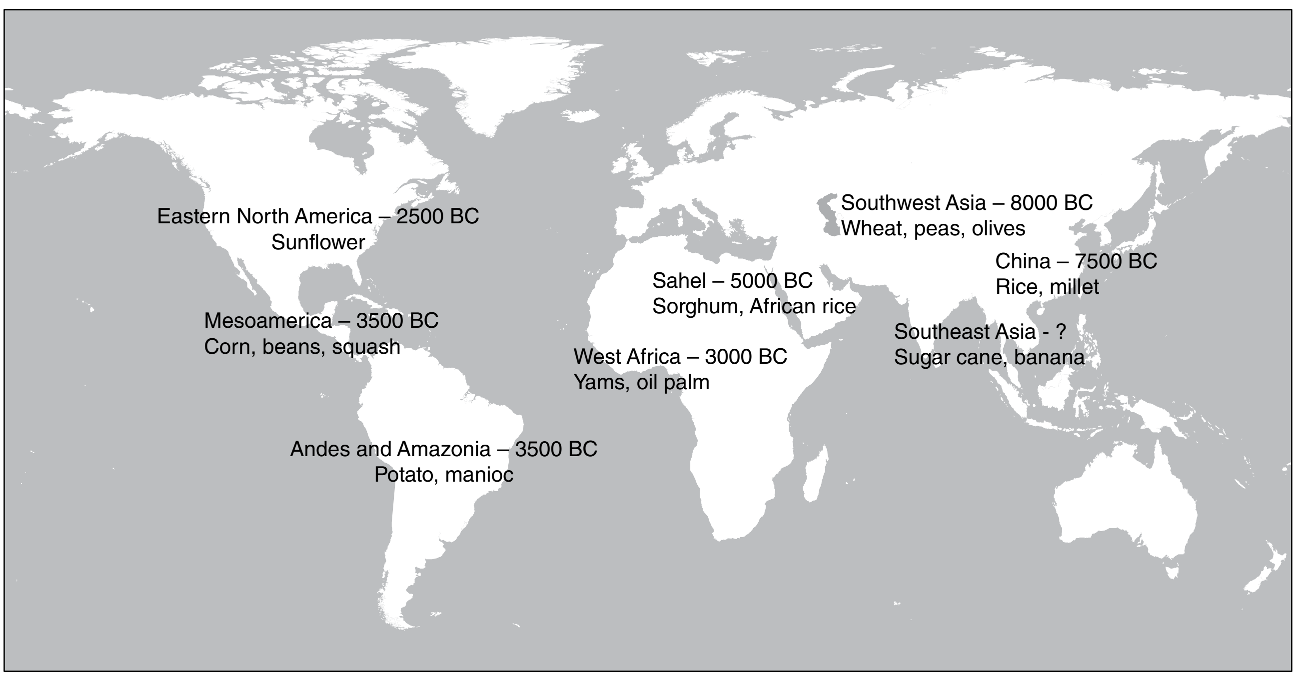


Figure 1.1 Early agricultural civilizations of the world and their main crops. *Source:* Adapted from mapsopensource.com under the terms of the Creative Commons Attribution Licence, CC-BY 3.

Box 1.2 Indigenous silvicultural systems of ancient civilizations.

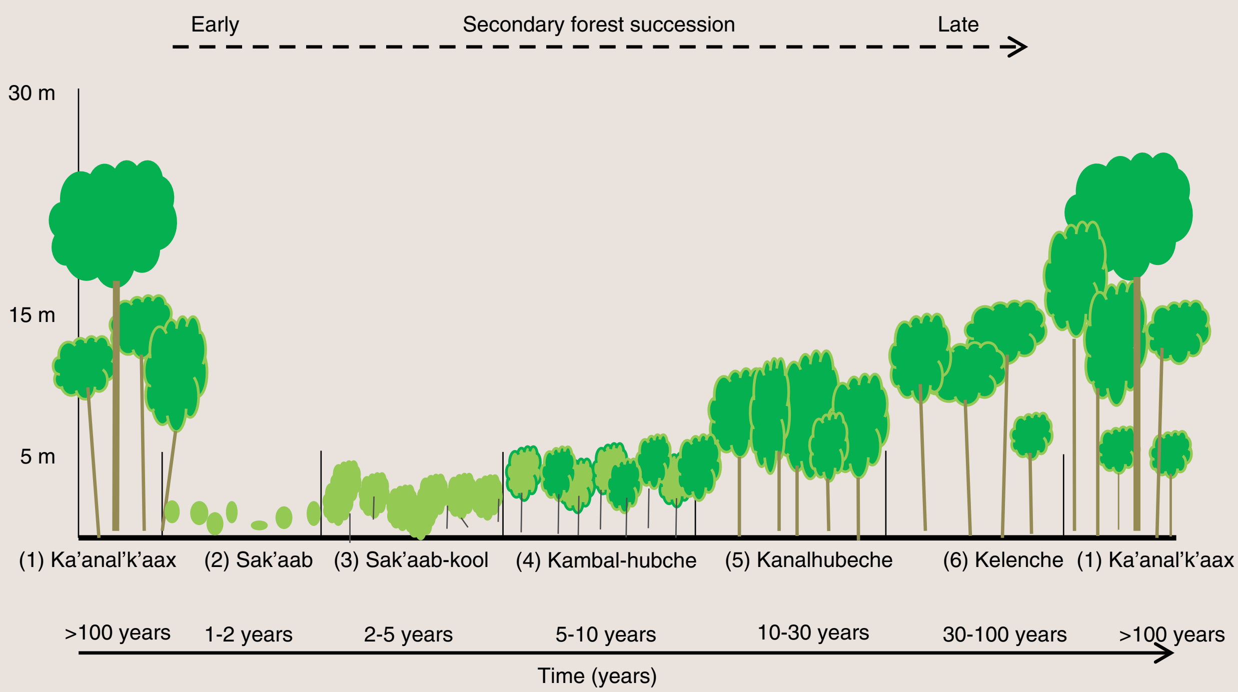
Maya of the Yucatan, Mexico

The Maya civilization of Mesoamerica can be defined by two periods: the pre-classic period (2000 BC – 250 AD) established the first complex cities and the cultivation of staple crops (maize, beans, squash, and chili peppers); and the classic period (250 AD – 1000 AD) which saw the rise of a large number of city states interconnected by trade highways. This period was the zenith of complex agricultural and silvicultural systems. Trees were incorporated into almost all components of an intensively managed landscape. Hydraulic systems were used to both drain and irrigate the staple crops of beans and maize. Swamps were drained and fields raised with trees planted along the bunds and the channels used for aquaculture. Upland slopes were terraced and irrigated for cultivation and shade trees used for stabilization and protection. Further away on poorer upland soils, the milpa swidden system (see Fig. 1) that is still used by the descendants of the Maya was widely practiced to cultivate crops (corn, beans, squash) for a short period of time. In preparation, second-growth pioneer species were slashed at about a meter high to open up the ground to sunlight. Annual crops were dibble planted for several years while the pioneers re-sprouted and were used as shade and fuelwood. Enrichment planting of cacao often follows annual crop cultivation using the shade of the second growth for establishment. Most milpas had an arboreal shelterbelt that was protected around the margin as a conservation strip. Around the households forest gardens cultivated a wide variety of fruit trees (*e.g., Brosimum alicastrum*, *Chrysophyllum cainto*, *Manilkara zapota*, *Spondias* spp.) and medicinal herbs and spices. These tree gardens were called Pet Kot. In addition, the Maya had sacred forests and groves around temples that were protected and where Maya harvested a variety of medical plants. Over one third of the flora have known medicinal value. The Maya civilization collapsed about 12,000 AD from unknown causes – possibly warfare, disease, or from land degradation and soil erosion or some combination. The second growth that has come back within the region is reflective of this historic land use dramatically enriched in species from purposeful Mayan silviculture.

For more information read: Gomez-Pompa, A. 1987. On Maya silviculture. *Mexican Studies*, 3(1): 1–17.

Sinhala of Northeastern Sri Lanka

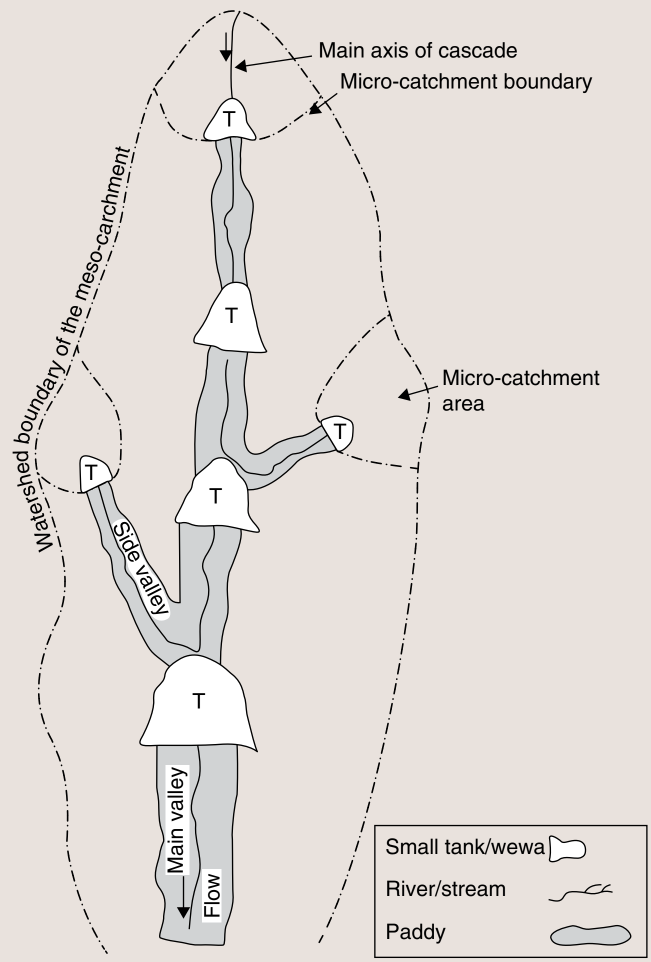
Southern India has a very sophisticated history of forest and crop cultivation dating back to 2000 BC. The start of civilization in northeastern Sri Lanka dates back to about 500 BC with the arrival of the Sinhala people and the Prince of Vijaya from North India. Northeastern Sri Lanka has a monsoonal climate that comprises a long dry season and a



Box 1.2 Figure 1 A diagram depicting Maya swidden succession. Maya succession nomenclature are (1) Ka'anal'k'aax: old tropical forest (30 or more years old); (2) Sak'aab (or Sak'ab): second year milpa; (3) Sak'aab-kool: Recently abandoned milpa; early succession; (4) Kambal-hubche': 5–10 years old succession; (5) Kanalhubche': 10–30 years old succession; (6) Kelenche': 30–100 years old succession; (3-6) Hubche': secondary vegetation. *Source:* Adapted from Gomez-Pompa, 1987.

Box 1.2 (Continued)

shorter wet season. The people learned to manage water by a complex system of reservoirs (called tanks) that were arranged as a cascade that comprised an interconnected series of tanks that reused water for irrigation within a single watershed and that gradually increased in size progressing from the upper to the lower parts of the watershed (Figs. 2, 3). These systems developed over a 2000-year period culminating in about 30,000 tanks in a dry zone area of 15,500 mi^2 (40,000 km^2). The undulating topography with its ancient impermeable metamorphic geology and relatively thin to bedrock soils that were weathered *in situ* make this landscape perfect for water capture and irrigation. The Tank Cascade System allowed two to three crops of rice to be cultivated per year in the lower lying land beneath each tank by a system of irrigation channels and fields. Some of the lower lying fields were purposely left for the birds to draw them away from those that were cultivated. The tanks themselves were lined with riparian forests and vegetation that served to protect the sides of the tank and to serve as a wind barrier. Potable drinking water was purified through a system of channels drawn from the tank separate from the irrigation systems. These channels flowed into small wetlands in which the water was cleansed of sediments and pollutants. The villages and houses were organized immediately outside but adjacent to the floodplain. Individual households had kitchen gardens and patios surrounding the house where many of the perennial light-loving shrubs (banana, plantains, citrus) and herbs (curry plant, cumin, cardamom) could be cultivated. Surrounding the kitchen garden, tree gardens of a variety of shade-loving long-lived species (mango, coconut, jak fruit, tamarind, areca palm) were grown for fruit and timber. Upstream and at higher elevations of the catchment areas beyond the tree gardens, second-growth forests were managed through swidden cultivation (called Chena) for upland dry crops, firewood, and medicinals. Beyond these second-growth forests, in the most remote and highest parts of each watershed catchment, existed relatively undisturbed forests whose main purpose was to yield subsurface water flow into the dry season through deep infiltration. These areas were carefully controlled by the community and by the temple monks. Many of these forests were regarded as sacred and completely protected from use.



Box 1.2 Figure 2 An example of a tank cascade for a single watershed in northeast Sri Lanka. *Source:* Geekiyanage, 2013. Reproduced with permission of Elsevier.

(*Continued*)

Box 1.2 (Continued)

Box 1.2 Figure 3 The ancient managed landscape of northeastern Sri Lanka. The tank cascade systems can be seen in the distance. Adjacent and downstream areas to the tanks are the cleared lands for paddy cultivation. The settlements with complex tree gardens are adjacent to the tanks on the upper ends along the margin in the middle of the picture. On higher ground is sacred forest associated with the temple that serves as watershed protection. *Source:* Mark S. Ashton.

farmers had grazing rights for livestock, rights to gather fuelwood and litter, and rights to some timber for building, but they were obliged to pay a fee for these rights. Similar land right arrangements between nobility and the peasants were present in northeast Asia (China, Korea, and Japan) during this time. Particularly innovative and forward-thinking nobles started the systematic and purposeful management of forests for timber on such lands as early as the 14th century in Germany (Nurenburg) and by the 16th century in Japan. Forests were divided into sections, with the ideas of sequentially harvesting for timber over time and purposeful regeneration. In the 17th century, the ideas of John Evelyn and Jean-Baptiste Colbert led to the first plantations in the British Isles and France respectively. Each of these men were sent by their respective governments to assess the depleted state of the forests in their countries.

Prior to the industrial revolution, one predominant form of silviculture and forest type was associated with permanent agriculture. These were coppice or sprout origin forests. Still throughout much of Africa, Asia, and Central America, forests and woodlands are all managed based on sprout growth to produce fuelwood for cooking and heating, litter and mulch for agricultural fields, timbers for buildings, artisanal wickerwork and poles and posts for farm infrastructure (Box 1.3). It is amazing that in this modern age of technology, the majority of the world's population still relies on fuelwood for energy and forest leaf litter as a source of soil fertilizer.

Silviculture as a Western Construct

It was with the birth of the industrial revolution, particularly in central Europe, that forest lands were decimated for timbers to support underground mining for coal, iron ore, and salt, and for fuelwood. This was to create charcoal to power the furnaces for the smelting of iron ore, evaporating water to extract salt, and to provide heat and cooking fuel for a burgeoning and urbanizing populace that had come for work in the cities. Whole areas of central Europe were converted from subsistence agricultural and coppice woodland systems to waste-

Box 1.3 A coppice and wood pasture system in medieval Europe.

Ancient wood pastures, often identified today by the presence of old pollarded "veteran" trees or land records, were common throughout Europe since at least the Neolithic Age. In England, documentation dates back 1200 years (Rackham, 1996). While the practice was largely abandoned several centuries ago, wood pastures do persist. While most were converted to other land uses, some have "infilled" with younger cohorts of trees and are now barely discernible, while others are preserved as living museums, and fewer still are actively managed as wood pasture.

A rich literature has accumulated, particularly in the British Isles, on the social and ecological history of these wood pastures (Fig. 1) and their role in a complex landscape of commons, forests, parks, and woodlands. The grazing of animals and growing of trees on the same land has been sustainably practiced for centuries (Rackham, 1998). The nuances of these pasture systems vary by region and make use of different species and techniques to meet location specific needs. Two broad categories of wood pastures can be distinguished: (1) coppice meadows and (2) pollard meadows (Hæggström, 1998). Coppice meadows are comprised of multi-stemmed trees that are cut at intervals of some decades to produce stakes, poles, firewood, and wood for carpentry. Hay is produced between the coppice trees. Livestock are often excluded from these meadows at least for a period of several years to give recently cut trees time to grow above the browse line. Pollard meadows are used to produce fodder from tree cuttings while livestock are allowed to graze between the trees. These trees are cut at 3–5 ft (1–1.5 m) to keep them safe from browse. Cuttings are often dried and stored as winter fodder or used directly. Shredding is an alternative pollarding technique where only the lateral branches are cut and the top of the tree left intact. Differences in pollarding technique arise from variations in species autecology and climate.

A case study by Bargioni and Sulli (1998) on the Valdagno farm on the eastern slopes of the Lessini Mountains, Italy provides an illustrative example of pollard meadow management. The local climate exhibits long, cold winters with short, hot summers and an annual precipitation of 58 in (1489 mm). The farm breeds cows and at any given time has 4–5 milking cows, 2–3 sheep, 25–30 chickens, and one pig. The 10–12 acres (4–5 ha) is 47% grassland, 29% wooded pasture, and 10% coppice woods with the remaining 14% split between high forest and farm infrastructure. The Valdagno farm faces constraints on its productivity. The 4–5-ha farm encompasses only 2 tillable hectares, which significantly constrains total productivity. To help overcome this limitation, vertical space is cunningly utilized to expand animal husbandry.

Between May and October, cows are grazed in the wooded pastures and excluded from the winter hay-producing meadows except for the time following the second mowing. The animals are sustained through the long winters with a mixture of meadow hay and tree fodder. Two kinds of fodder

Box 1.3 Figure 1 An ancient sweet chestnut (*Catanea sativa*) wood pasture in Monmouthshire, Wales. *Source:* A. Miles, 2012. Reproduced with permission from A. Miles.

(*Continued*)

Box 1.3 (Continued)

are produced on the farm. *Broco* is produced by shredding leaves directly from the tree for immediate use, while *frascari*, faggots of branches and leaves, are collected and preserved for winter nourishment. Ash (*Fraxinus* sp.) is the most important species for fodder production, while alder (*Alnus* sp.), poplar (*Populus* sp.), and hazel (*Corylus* sp.) are commonly used to produce *broco*. Beech (*Fagus* sp.) is a common spring fodder as its shoots appear before grass emerges from under the forest cover.

Pollarding commences when trees are between 7 and 12 in (18–30 cm) in diameter and are 7–8 years old. At this time, the leader is cut causing the stem to bifurcate and all branches along the stem are cut at 6–8 in (15–20 cm) from the main stem leaving stubs. These stumps will produce the *frascari* and can be used as ladder rungs for the farmer to climb the tree in the future. Each year, *broco* is produced from the top crown while every third year the stems, which are 1.5 m long at this point, are cut to produce *frascari* bundles in late August. Trees are cut and replaced when their tops stop producing leaves, usually at a diameter of 10–12 in (25–30 cm). These pollarding techniques have enabled the Valdagno farm to take advantage of vertical space and sustain itself despite a shortage of tillable land.

lands in order to supply the wood necessary for this development. As a result in the state of Hesse, Germany, George Ludwig Hartig envisioned the first school of forestry for reforestation in 1787. Later, Heinrich Cotta, who has been attributed the name "pioneer of forestry", started a forestry school in 1811, in the town of Tharandt, near Dresden, Saxony. His school and his teaching became the foundation for German forestry and its later influence around the world. The notion of teaching forestry and the idea of forestry schools spread in the late 18th century to Russia, Austria, Sweden and France. Spain opened its first Forest Engineering School in 1844 in Madrid, and the British government commissioned Sir Dietch Brandis, a student of Cotta, to start the Indian Forest Service and a School of Forestry at Dehra Dun (Box 1.4).

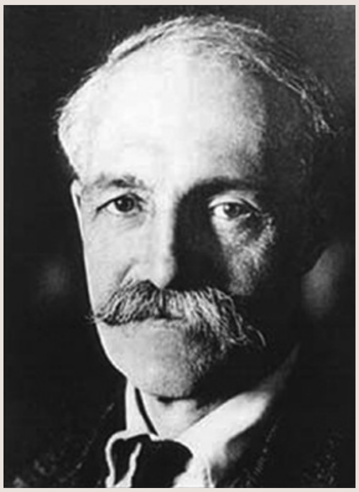
Box 1.4 The development of the Indian Forest Service and Sir Dietrich Brandis.

Sir Dietrich Brandis was born in Germany where he studied botany at Copenhagen, Göttingen, Nancy, and Bonn (Fig. 1). At the behest of Lord Dalhousie, Governor of British India, he was asked to take on supervision of the famous native teak forests of Burma in 1856 (Milward, 1947, Underwood, 2013). He developed the "taungya system" whereby villagers were allowed to cultivate vegetables in between planted trees and in return they weeded and protected the new plantings (Fisher, 1910). This has now been repeated worldwide and is an agroforestry practice that can involve communities in tree planting. In 1864 he became the first Inspector General of the Indian Forest Service. He founded the Imperial Forest School at Dehra Dun in 1878 to formally educate the local peoples in scientific forestry (Fisher, 1904). He wrote a treatise on Forestry in British India and the book "Indian Trees" and documented and described sacred groves throughout India. He was among the first to acknowledge the relationship between forest protection and involving local peoples. For his service to the British Empire he was knighted and retired back to Germany where he met future German foresters as well as Gifford Pinchot and Henry Graves. Pinchot relied on Brandis for advice in setting up the nascent US Forest Service. He died at the age of 83 in 1907. The model for modern forest management in the United States, Britain, and Australia lies in the practices of the Indian Forest Service (IFS) that Brandis started (Pyne, 1997; Oosthoek, 2007).

Box 1.4 Figure 1 Sir Dietrich Brandis. *Source:* Forest Research Institute, Dehra Dun, India.

Box 1.5 A brief biography of Gifford Pinchot.

Gifford Pinchot was born in 1865 and grew up in Simsbury, Connecticut (Fig. 1). He attended Yale College. After graduating from Yale he studied forestry at the French National School of Forestry in Nancy. Upon his return in 1892 he was hired by George Vanderbilt, a wealthy railroad tycoon, to manage the Biltmore Forest Estate outside of Asheville, North Carolina. This was under the suggestion of the renowned landscape designer, Frederick Law Olmstead (Miller, 2001). He was succeeded by Carl A. Schenk, a German forester, who set up the first School of Forestry at Biltmore in 1898, a few weeks prior to when Bernard Fernow, another German forester, started the New York State College of Forestry at Cornell University. Gifford continued on to succeed Fernow as the Chief of the Division of Forestry that same year, 1898. In 1900 he and his father, James, endowed Yale to create and start the first postgraduate program in forestry at what was then called the Yale Forest School and is now the Yale School of Forestry and Environmental Studies (Miller, 2001). He seconded two US forestry division personnel to be its first Dean, Henry Graves, and faculty member, James W. Toumey. Toumey went on to become a founding member of the Ecological Society of America and wrote the first forest ecology text for the country (Pinchot, 1998). In 1905, Pinchot became the first Chief of the newly made US Forest Service at the behest of then President Theodore Roosevelt. Pinchot is largely responsible for developing the administrative foundation of the Forest Service and the creation of the National Forest System which now comprises the majority of public lands in the US (Meyer, 1997; Miller, 2001). After leaving the Forest Service he went on to become a two-time governor for the state of Pennsylvania. He died in 1946.



Box 1.5 Figure 1 Gifford Pinchot. *Source:* US Forest Service.

By the end of the 19^{th} century the newfound profession of forestry was ripe for development in North America. Gifford Pinchot (Box 1.5) had gained his forestry training in Germany and France. Several German foresters, upon invitation, had emigrated to the USA to introduce forestry. Two such German foresters, Carl Schenck and Bernard Fernow, respectively, started the Biltmore Forest School in Asheville North Carolina, and the New York State College of Forestry at Cornell University in 1898.

Silviculture as a Current Practice

Current silviculture is a much more complex and varied practice than at any stage in its development history. In the more remote forests of tropical Africa and the Amazon, people still practice the silviculture associated with swidden systems. In many populated rural regions of the tropics, coppice systems, once widespread in Europe and northeast Asia, still predominate. Much of the developed world now has intensive plantation systems for wood production, and considerable second-growth forest on more marginal sites that have returned after agricultural abandonment. These forests are managed for multiple benefits often using complex natural regeneration methods.

Silviculture and its association with long-term investment for future products and services desired by the landowner and by society must have social stability. This means that stability and clear recognitions of land tenure, environmental laws, and strong and diverse markets must exist; only under these conditions can silviculture flourish. Without this security it is unlikely to be practiced with any surety or investment of purpose because of a reluctance to invest in the forest for the future (see Fig. 1.2). The most sophisticated silvicultural practices are at both ends of the development continuum. On the least developed end, people can practice silviculture where their land tenures and ways of life, though not necessarily officially codified, have been untouched by the process of development. On the most developed end of the continuum, silviculture can be practiced where economies have developed to create strong values for both services and products from the forest, with healthy and diverse markets, strong enforceable regulations in land use, and formal rights to land tenure. The most difficult place along the development continuum is in the middle, where countries or regions are experiencing social transition like colonization, economic development, poverty alleviation, and political democratization. In these cases, silviculture can be practiced but with a

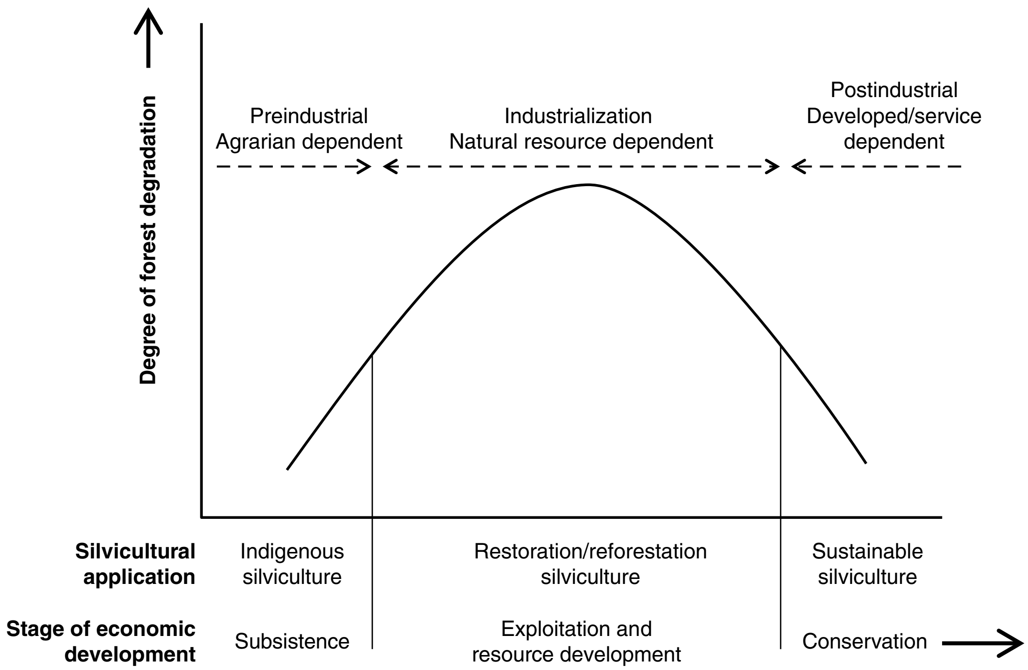


Figure 1.2 Economic and social development process leading to a developed economy and the forms of silviculture practiced. *Source:* Adapted from Panayotou and Ashton, 1992.

tendency toward risk-averse investment in time and labor and with a focus on the short term.

The Philosophies of Silviculture as a Practice

Ecological Technology

The necessity that nature should be understood and emulated does not mean that silviculture should slavishly follow either the reality of natural processes or abstract theories about them. Most forests live longer than people. It is difficult to recognize that the natural disturbances that renew forests, often after intervals of centuries, are usually big, such as fires, windstorms, and insect outbreaks (Oliver, 1981; Kimmins, 1987; Oliver and Larson, 1996). Some forests are slowly and continuously renewed by minor disturbances, but these are far from being the norm. The various patterns in the development of forest vegetation over time and after disturbance are discussed in Chapter 4 on stand dynamics.

The web of life is so complicated that it is easy to argue that humans should do nothing to the forest for fear of doing something wrong. However, because of the exploitation of so much of the world's natural resources, humans must develop solutions to counteract the destruction of these natural resources. Tightly controlled **forest research experiments** are the standard for creating new knowledge in the forestry field, but they are also very expensive. Thus, society requires practitioners of forest science to act without full knowledge. The best that can be done is to proceed by **adaptive management**, in which action can be taken on the most complete knowledge available. This approach has become quite useful. The three steps include:

1) **test assumptions:** use the current knowledge regarding the specific site; determine and collect monitoring data to determine if the assumptions are correct;
2) **adaptation:** change assumptions if new information has been found from the monitoring and project experience;
3) **documentation:** describe the planning and implementation for the specific site, and maintain records of the results.

Silviculture is conducted on the basis of ecological principles. The goods and benefits that flow from forests with proper, long-term management depend on living processes and are thus renewable to the extent that basic productive site factors are maintained and they can even be increased if these factors are permanently improved.

The wood produced by forests is the most important structural substance in human use. Unlike mineral or agricultural materials, its production requires much less energy and does little that would damage or pollute. In fact, the growing of wood increases the stock of resources even as it cleans both air and water. If forest

vegetation were more efficient in yielding human food and in concentrating sources of fuel, the future of the world ecosystem would be much brighter for the human race. It is therefore ecologically ignorant to assume that "saving forests" by substituting wood with substances produced with fossil fuel from mineral resources benefits any human-dominated ecosystem.

Economic and other social factors also affect the silvicultural policy of any given area. The simple objective is to operate so that the value of benefits derived from a forest should exceed the value of efforts expended. The most profitable forest type is not necessarily the one with the greatest potential growth or the one that can be used or harvested at the lowest cost. One must also consider the silvicultural costs of growing the crop or maintaining the stand and the prospective losses to insects and disease. In fact, it is usually the insects, fungi, and atmospheric agencies that ultimately show where silvicultural choices have run afoul of the laws of nature. The majority of the best choices are imitations of those natural communities.

It is also not entirely safe to accept the success of modern agriculture as justification for highly artificial kinds of silviculture. The environment of a cultivated field is much more thoroughly modified and readily controlled than that of a forest stand. Furthermore, forest crops must survive winter and summer over a long period of years, whereas most agricultural crops need survive only through a single growing season. One disastrous year harms the production of just one annual crop, but it can destroy the accumulated production of many years in a stand of trees. Neither economic nor ecological principles permit the forester to engage in the wholesale, routine use of pesticides and fertilizer on which intensive agriculture often rests. Any silvicultural application of refinements borrowed from agriculture must be combined with all the kinds of measures appropriate to the intensity of agriculture imitated. Forestry can profitably borrow much more than it ever has from the science on which modern agriculture is based, but there is little place for uncritical imitation. In addition, silviculture, even in the most intensively managed systems, needs to balance other multiple values that a forest must provide to society (clean drinking water, biodiversity conservation, recreation). Intensive agricultural systems often over-ride or ignore these values.

Some silvicultural measures depart drastically from natural precedent. These usually involve the introduction of exotic species or the creation of communities of native species unlike anything that might come into existence naturally. Departures of this sort cannot be thoughtlessly condemned but should be viewed with reservations until they have been tested over long periods. Otherwise, most of the choices can be thought of in terms of the degree to which natural processes are accepted or arrested, pursued or reversed.

Relationship with Forest Management and the Social Sciences

The decisions made in silvicultural practice are based as much on economic constraints and social objectives as on the natural factors that govern the forest. Recognition of societal objectives and limitations in any given case reduces the silvicultural alternatives that need be considered. Even though intelligent application of silviculture can make a very positive contribution to the management of forests, it is ultimately guided by strategies for solving problems associated with the social sciences. Matters that involve social and economic considerations are more broadly dealt within the interdisciplinary field of forest management. Forest management is concerned with planning, stakeholder analysis, economic analysis, conflict mediation, harvest scheduling, and the administrative aspects of the whole forest area (Davis and Johnson, 1987; Davis *et al*., 2005; Bettinger *et al*., 2009). The field of forest policy deals more indirectly with the effects of sociological and political phenomena, as well as economics, on the uses and governance of forests.

Silviculture and forest management are therefore interdependent, and not parallel approaches to the same problem. Because of its dominant concern for efficient application of the natural sciences, silviculture is as "practical" as forest management, with its tendency toward preoccupation with economic considerations. No management plan is better than the silviculture it stipulates, nor is any silvicultural treatment better than the usefulness of the results it produces for management.

Silviculture and the Long-Term Economic Viewpoint

It is said that money does not grow on trees, but it is the bane of forestry that the popular view is that trees exist but do not grow. The short-term outlook of conventional economic theory holds, in effect, that the silviculturist cannot win in growing a forest to reap the long-term benefits while certain naturalistic ecological theories warn against trying. The economic timescale of forestry is so vast and unique that to many investors it really is not profitable.

There is scarcely any part of forestry in which this issue must be faced more squarely than in silviculture, especially when investments in establishing or treating young stands are considered. It takes a certain kind of ambivalence to keep the economics of forestry in perspective. The decision to practice forestry is usually a matter of ethics, politics, and social concern for posterity. It is usually not one of conventional economics unless the product grown is highly valued and grown like an agricultural crop, which in reality is refined to a narrow set of sites and circumstances. In general it is the failure of economics and society to properly value the multiple service

values that forests provide that is the most detrimental to the sustainability and financial integrity of forest management in the long run. However, once the decision is made, it becomes logical to apply economic analysis to determine how best to execute the details. Any conflict is not between "silviculture" and "economics" but between the long-term economic viewpoint of forestry itself and customary short-term outlooks on financial matters. In the long run, short-sighted silviculture and poor environmental management become unprofitable. A forester should be extremely cautious of allowing economics to over-ride silvicultural principles that relate to the constraints of site and ecology. It will usually mean a much larger unrecognized financial disaster for the future with the depletion of the soil and forest resource and little ability to restore this resource for the benefit of society.

The holding of land for future production of wood, non-timber forest products, or other service benefits involves silviculture, even if nothing more is done than to let nature take its course and to harvest trees occasionally. Ownership incurs costs, and these constitute investments in the future even if nothing is invested in treatments to increase future production.

Foresters must ensure that money is spent very efficiently because funds are rarely sufficient for all the silvicultural work likely to be worthwhile. In any situation, it is logical to first apply those treatments that will yield the greatest increase in value of benefits per dollar of investment.

The first stage in the evolution of silvicultural practice is where continued production is actively sought but without any monetary investment (Barnes *et al.*, 1998). This "no-investment" silviculture places emphasis on treatments that can be accomplished by removing merchantable timber without significantly increasing harvesting costs. The removals cannot exceed the productive growth capacity of the forest. Some forests are sufficiently easy to control and give reasonably good results. This kind of silviculture is practiced over wide areas of temperate and boreal native forests and will likely continue for a long time. The idea of taking values out of the forest without really reinvesting anything in future production has a powerful appeal. It almost completely dominated American silviculture for many decades. There are still many instances in which it is consciously or unconsciously regarded as the only economical alternative. Tropical forest has been managed in this way under so-called selective logging but the harvest of timber has generally exceeded the productive growth capacity of the forest, leading eventually to a depletion of standing timber value and land conversion to agriculture.

Orderly policies of long-term investment in silviculture emerge if economic conditions and natural productivity are favorable, and provided that adequate management experience has developed within the country or region. The kind and amount of investment are limited only by the economic law of diminishing returns. The actual amount expended on this type of silviculture varies widely but can be considerable. Currently, growing and cultivating forests in the developed world, such as in the US, are considered attractive, long-term investments that can provide multiple economic values. The "free" wood of cutting old growth is no longer considered acceptable. Old growth is better preserved for its intrinsic value and for the multiple service benefits that it provides to society.

Variations in Intensity of Practice

The amount of effort expended on the treatment and care of stands – that is, the intensity of silviculture – varies widely, depending chiefly on economic circumstances. The converse of **intensive silviculture** is **extensive silviculture**. The degree of intensity is usually estimated in terms of such things as the amount of money invested in cultural treatment, the frequency and severity of cuttings during the rotation, and the amount of monetary returns accorded to future returns relative to immediate returns. This leads to a debate on how forests should be managed. Some argue that intensive management only for timber on the appropriate sites will conserve most other forests as reserves (Binkley, 1997; Sedjo and Botkin, 1997). Others argue for a more extensive management regime in which timber is a more intimate component of other social and product values (Panayotou and Ashton, 1992; Oliver, 1999).

In reality the appropriate intensity of silviculture varies with accessibility, markets, site quality, management objective, and nature of ownership. The proper level often must be chosen specifically for each stand because the application of a single treatment intensity will not give optimum results throughout a given forest, unless it is exceedingly small and uniform. The more favorable the combined economic effect of all factors, the higher the appropriate level of intensity of silviculture. The place for extensive silviculture is found in remote areas on poor sites, or where owners are not willing or able to make more than minimum investments. It often plays a role where timber production is secondary to other purposes of forest management. Much of the world's forests are now to be managed in this way since all of the best land has now been largely converted to permanent agriculture (Fig. 1.3; Table 1.1).

In the past, American forests have been exploited in such a manner that the poorest and most ill-treated stands are often found on the best sites and in the most accessible areas, such as those along permanent roads. This situation arises because the best and

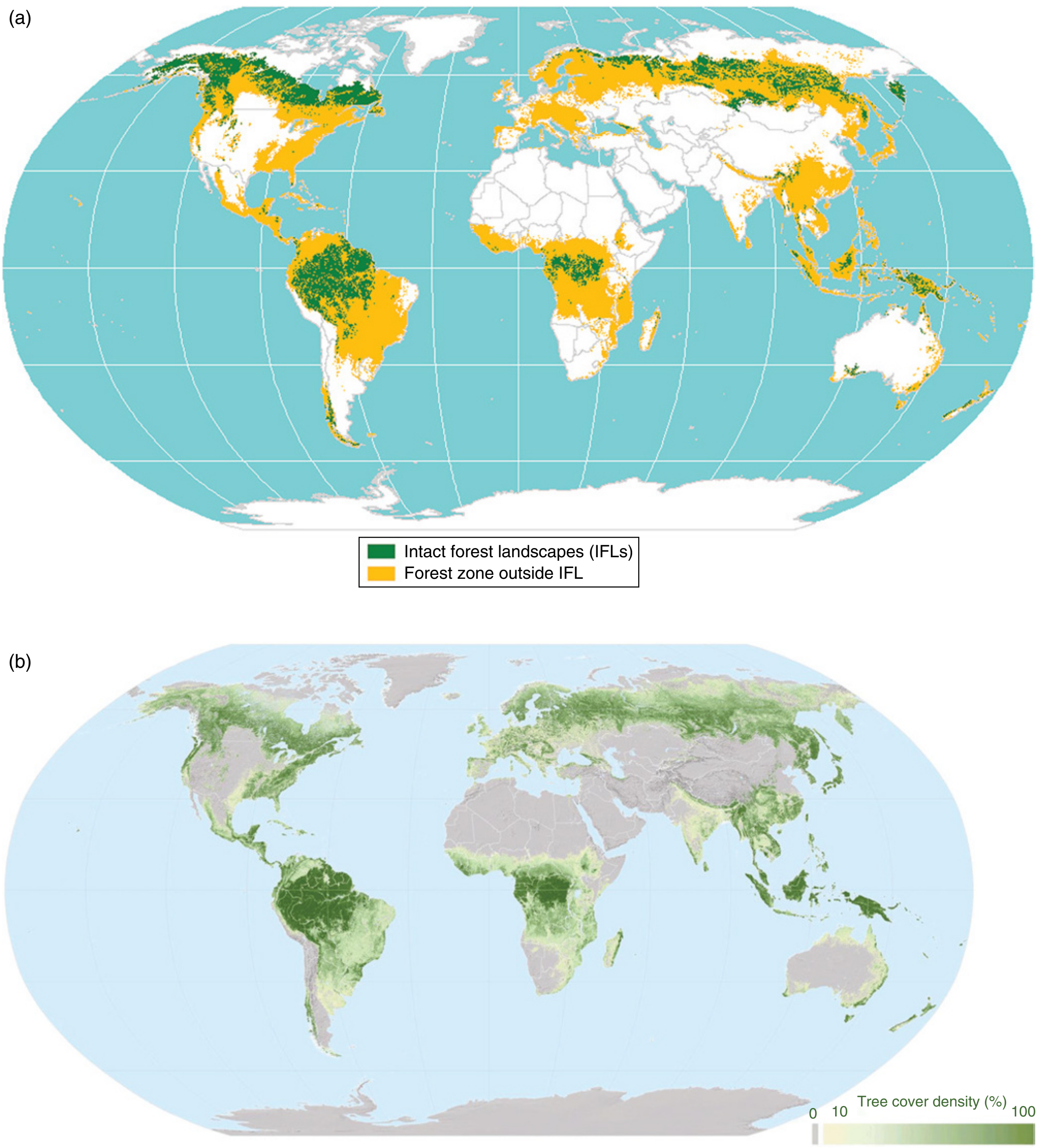


Figure 1.3 **(a)** A global depiction of the world's original forest (orange shading) and current undisturbed forests that have had little human impact (green shading). *Source*: Potapov, 2009. **(b)** A global depiction of the world's current forest cover (as measured by tree density) including undisturbed and second growth forests that have been logged or reverted back post land clearance for agriculture. *Source:* FAO, 2010. http://www.fao.org/forestry/fra/80298/en/

most conveniently located stands have been exploited first, most heavily, and most frequently. Ultimately, high-intensity silviculture should be practiced in many of these situations. Permanent roads and good markets for a diversity of forest products do not automatically ensure optimum practice, but they are essential to generate income to profitably pay for the intensive management.

Table 1.1 Hectares[1] of land by geographic region of the world's forests. Forests are defined here as woodlands and closed canopied forests; secondary forests of post agricultural origin or that have been logged and undisturbed forests. Primary undisturbed forest areas and their percent of total forest area are provided in parentheses.

Region	Forest area (in 1000s of ha)	% Land area
Africa – TOTAL	**635,412 (37,669)**	**21.4 (8.7)**
North Africa (dry temperate woodland)	131,048 (13,919)	8.6 (11.9)
East and south Africa (dry tropical woodland)	226,534 (12,241)	27.8 (5.7)
West and central Africa (wet tropical forest)[3]	277,829 (11,510)	44.1 (11.6)
Asia – TOTAL	**571,577 (87,526)**	**18.5 (15.3)**
Western and central Asia (dry temperate woodland)	43,588 (2,810)	4.0 (6.4)
East Asia (temperate broadleaf/coniferous forest)	244,682 (21,808)	21.3 (8.9)
South and southeast Asia (wet and dry tropical forest)[4]	283,127 (62,908)	33.4 (22.2)
Europe – TOTAL (temperate broadleaf/coniferous)[5]	**1,001,394 (263,948)**	**44.3 (26.8)**
North America – TOTAL	**705,849 (311,656)**	**32.9 (44.3)**
Caribbean (wet and dry tropical forest)	5,974 (60)	26.1 (1.5)
Central America (wet and dry tropical forest)	22,411 (9,139)	43.9 (40.8)
North America (temperate broadleaf/coniferous)[6]	677,464 (302,456)	32.7 (44.6)
South America – TOTAL (wet and dry tropical forest)[7]	**831,540 (601,689)**	**47.7 (76.8)**
Australasia/Oceania (temperate and tropical forest)	**206,254 (35,275)**	**24.3 (17.2)**
WORLD	**3,952,025**	**30.3 (36.4)**

1) 1 hectare = 2.471 acres
2) FAO statistics are fraught with potential error but it is the best estimate available. The statistics are dependent upon proper interpretation and supply of information by government officials of each country
3) Most of the primary forest that remains is in the central African country of the Democratic Republic of Congo
4) Most of the primary forest that remains is in Laos and Indonesian Borneo
5) By far the largest proportion of both forest and primary forest is in the Russian Republic
6) By far the largest proportion of primary forest is in the Canadian boreal
7) By far the largest proportion of primary forest is in the Amazon (Brazil, Peru)

Source: FAO[2], 2005. Reproduced with permission from FAO.

The intensity of timber-production silviculture depends in large measure on the nature and objectives of ownership. Variations in the species and sizes of trees desired may necessitate different procedures on adjoining lands that are fundamentally similar. Stability or longevity of ownership also controls intensity of silviculture. Large corporations and public agencies, which are relatively immortal, are in a far better position to practice intensive silviculture than individuals or small corporations of uncertain stability, though the idea of the immortal corporation has been turned on its head to some degree. Such corporation forestlands have now mostly been sold and are now managed by timber investment management organizations (TIMOs) for a variety of forest investors, such as pension fund investments that generally have a more short- to mid-term perspective.

The intensity of silviculture often depends on the extent to which the owner processes the wood grown in his forest. The more the raw material is processed to its final product, the greater is the ability to capture the "values added" by increases in intensity of practice in the woods. Prices for stumpage (that is, standing trees), do not necessarily reflect all the values that silviculture adds by improving the quality of wood. Therefore, the owner who cannot do more than sell stumpage may not be able to practice silviculture as intensively as owners who also harvest, manufacture, and sell the final product. This relationship is modified, however, by the ability and willingness to make long-term investments. For example, public forestry agencies usually confine their operations to producing stumpage. They may, however, practice intensive silviculture without concern for profit on their investments in order to discharge their long-term responsibilities to the national economy.

Philosophical Application of Silviculture

Given the perspectives in the preceding sections of this chapter, it is clear that the practice of silviculture does not consist of rigid adherence to any set of simple or detailed rules of procedure. For example, this book cannot be used as a manual of operations. Many of the cutting techniques are described in simplified form. Absent are many of the refinements and modifications necessary to accommodate the special circumstances and local variations encountered in practice. Each procedure described in the book is merely an illustration intended to demonstrate the application of a set of treatments designed to meet a uniform set of circumstances. Even though uniform stands have important advantages that make them worthy of creation, the stands encountered in the field will likely lack uniformity and thus call for variation in treatment.

Any consideration of silviculture covers a variety of treatments wider than is likely to be practiced in any locality at a particular time. In times when all the forests of a locality are immature, silvicultural practice may be limited to intermediate cuttings. Anything connected with regeneration may be limited to the reforestation of vacant areas. In localities where it is customary to secure regeneration by planting, the forester may regard methods of natural regeneration only as matters of intellectual exercise. Conversely, where planted stands are an anathema or owners are not ready to invest in them, only natural regeneration may seem important. At times and places where economic conditions support only the crudest kind of extensive silviculture, intensive treatments may seem visionary indeed.

This book contains a wide variation in intensity of silvicultural practice because an attempt is made to describe all known techniques that seem applicable in any significant forest area, especially of North America, within the near future. The procedures characteristic of the more intensive kinds of silviculture cannot be described as briefly as those associated with extensive silviculture, and so they get more attention. This does not mean that a management program must include a long series of different treatments to be silviculture. Some of the most astute silviculture is the kind conducted at low intensity in which much is accomplished with a limited amount of treatment.

The student forester interested in only one particular region should not limit their attention to the kind of silviculture currently practiced there. Foresters move, times change, and ideas from other places are often as fruitful as the indigenous ones. Scientific knowledge and technology also grow at an accelerating pace. The demands that society places on forests continually increase even as that same society places increasing restrictions on the ways of meeting the demands.

In many places, the impractical or impossible of 20 years ago is the routine – yet may prove to be the naive, illegal, or inadequate a decade in the future. Because of cutting and growth, the forests of a locality often change, and this calls forth new methods of treatment. This is especially true in North America, where the forests of localities tend to be in uniform condition, usually because in the past they were all cut over or cleared for agriculture in a short space of time. This book may seem to contain more techniques and ideas than a forester might need in a professional lifetime. Although some may go unused or quickly become outdated, there are really only enough to provide a start.

It is not enough for the forester to know what to do and how to do it. The important questions in silviculture begin with the word “why”. As in other applied sciences, action proceeds from the knowledge represented by the answer, or sometimes the merest inkling of an answer. The forester can find as many solutions in the woods as in the printed word. However, it is necessary to ask oneself the questions that generate the solutions and also to be ready to take the time to observe how the flora and fauna of the forest develop over time.

Silviculture as a Body of Knowledge

Silvicultural Literature

Modern silviculture literature was originally based on a series of treatises that were careful descriptive observations on the nature of light within a forest, the concept of shade tolerance, and on the growth of trees for the propagation of timber (Evelyn, 1664). Such books originally served as the core knowledge base for the early development of silviculture that Hartig (1808) and Cotta (1817) systematized into a discipline. All of this literature came before the German scientist Ernst Haeckel first defined the discipline of ecology in 1866 as “Ökologie”. Ecology (from Greek: οἶκος, “house”; -λογία, “study of”) is the study of interactions among organisms and their environment. As a science it now serves as the foundation for silvicultural application. But ultimately, silviculture goes beyond ecology as an applied discipline driven by social values, as James W. Toumey states so eloquently in his first forest ecology text for North America (Toumey, 1928).

Ralph Hawley wrote the first silviculture text for North America in 1921. It was directly modeled after the German texts and silvicultural systems of the day. This book is the direct lineage of Hawley’s 1921 book, that then evolved to Smith in 1954 (Hawley and Smith, 1954), and to us (Ashton and Kelty) in the 9th edition (Smith *et al*., 1997). As the 10th edition, this book has evolved a decidedly more nuanced and more North American perspective on

silviculture based upon much more concrete ecological theory and a more sophisticated understanding of social and ecological circumstance. Each chapter of this book ends with a listing of the references cited in that chapter. These references are the most significant and relevant to the topics discussed. Other books that should be recognized as significant regional or resource issue contributions upon which this textbook is based are Kevin O'Hara's 2014 book on *Multiaged Silviculture* and the book by Tappeiner *et al.* (2015) on *Silviculture and Ecology of Western US Forests*, and the work by Savill and colleagues on plantation forestry (Savill *et al.*, 1997). Other texts that should be recognized in the English-speaking literature are works by Daniel *et al.* (1979), Mathews (1991), and Nyland (2016).

The use of computerized information-retrieval systems is growing rapidly. More detailed information and many additional literature references about silviculture in the United States can be obtained from consolidated publications. In *Regional Silviculture in the United States* (Barrett, 1994), various silviculture professors have written about their localities. Research scientists of the US Forest Service (Burns, 1983; Burns and Honkala, 1990) have summarized information about the ecological characteristics of tree species and about the silviculture of the important forest types. One advantage of these sources is that they will help locate many of the large numbers of publications issued by research and extension agencies of governments and universities.

The *Forestry Handbook* of the Society of American Foresters (Wenger, 1984) presents much information about silviculture and closely associated topics, as do similar compendia designed to help the practicing foresters of a locality. The written word can bring the forester ideas from distant places. Not all of the problems of growing loblolly or ponderosa pine have to be solved exclusively by study of these individual species. Much has also been learned about the silviculture of pines in Finland and Australia; knowing about teak in Asia may also help. In fact, new and useful insights often come faster from distant sources. Most of the world literature of forestry is in English, although English-speaking forestry students should be more ambitious about mastering other languages.

A forester should not read about silviculture just to absorb information. Reading should be a stimulus to thought, a way of synthesizing new patterns of understanding, and of both expanding and testing ideas. It can make comprehension of processes seen in the woods surer and more serviceable.

Current Research Issues

The research and topic areas that are at the forefront of silvicultural research are diverse. In the last 30 years the concept and paradigm of stand dynamics have advanced silvicultural thought on how to treat mixed stands (Oliver and Larson, 1996) (see Chapter 3). This work continues to be pushed and elaborated upon by quantifying relationships that were only conceptual and qualitative such as our understandings of self-thinning and growth-and-yield (O'Hara and Gersonde, 2004). Work has moved forward especially on our understandings of how intimate mixtures of tree species grow in time and space (O'Hara, 2014).

The explosion of computer technology has provided a whole new field of quantifying space and time at stand and landscape scale models of treatments and management impacts (Bettinger and Sessions, 2003). In the last 20 years, a great deal of work has advanced modeling technology for silvicultural application (Pacala *et al.*, 1996; Vanclay and Skovsgaard, 1997).

A third topic is that our understanding of species and structural diversity of forests has also progressed. In the last 20 years, multiple ecological theories have been tested and explored around density dependence, intermediate disturbance, and niche hypotheses, for example. All are providing stronger theoretical arguments for applying silvicultural treatments judiciously based on ecology (Wright, 2002; Puettmann, Coates, and Messier; 2012; O'Hara, 2014) (see Chapters 5, 11, 13, and 28).

A fourth area has been the never-ending work that focuses on reforestation, planting technologies, and forest restoration, now centered particularly in the tropics (Ashton *et al.*, 2014; Griscom and Ashton, 2011) and within North America, particularly in the inland west (Fule *et al.*, 2001; Baker, Veblen, and Sherriff, 2007; Stanturf, Palik, and Dumroese, 2014). This is an old theme that continues to advance given its continuing dominance as an ecological and social issue around the world (see Chapters 16 and 25).

Fifth, great strides have been made in understanding the constraints and drivers of forest productivity, particularly in plantation systems focused on timber, another long-lasting theme of research (Fox, 2000; Fox, Jokela, and Allen, 2007) (see Chapters 16, 18 and 30).

Sixth, given the role of fire, fuels, insects, and climate change in the western USA, understanding this triad of relationships and drivers is critical toward restoring fire and forest health back into more resilient forests that are currently fire and insect prone (Dale *et al.*, 2000; Logan, Regniere, and Powell, 2003; Stephens *et al.*, 2012) (see Chapters 26 and 27).

Finally, a good deal of attention has been focused on the non-monetary service values that forests and trees provide. Whole new themes on urban trees and forests (Dwyer *et al.*, 2000), forest watersheds and drinking water supplies (Naiman, 1992; de la Cretaz and Barten, 2007), forest carbon and climate mitigation (Amato *et al.*, 2011; Ashton *et al.*, 2012), and bioenergy and wood technologies that substitute for other more energy intensive products (Dickman, 2006) have all been strong areas of research focus.

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2

Silviculture and its Place in Managing Current Forests and Woodlands

Introduction

This chapter provides an introduction to the book and its contents. It first defines the purpose of silviculture in context with examples of its application to current resource issues. The scope of silviculture and the use of its terminology is then described by providing the overarching theme that silviculture should: (1) imitate as much as possible the processes of nature, and (2) maintain and protect the inherent productivity of the site. Within this construct there are four guiding principles that silviculture can potentially strive to achieve, given both social and economic objectives and values. They are: (1) control structure and process; (2) control composition; (3) control stand density and spatial arrangement; (4) control rotation length, harvest intervals, and the life cycle of the forest. Then a framework is described to implement these principles within the construct of emulating nature and maintaining site productivity. This is done by: (1) defining the spatial scale at which silviculture is applied by introducing the concept of the stand; (2) defining the two basic sets of silvicultural treatments applied within stands, namely: regeneration methods and post-establishment treatments; and (3) defining treatments to the individual tree (e.g., pruning).

The Purpose of Silviculture Today

Definition of Silviculture

Silviculture has been defined in various ways, including the art and science of producing and tending a forest for the various social and economic values demanded by individuals and society. It has also been defined as the application of knowledge of autecology or silvics in the treatment of a forest. Finally, it has been defined as the theory and practice of controlling forest establishment, composition, structure, and growth. Since silvicultural practice is applied forest ecology, it is also a major part of the biological technology that carries ecosystem management into action.

Silvicultural practice consists of the various treatments applied to forests to maintain and enhance their utility or service for any purpose. The forester must analyze the natural and social factors that affect each stand, and then devise and conduct the silvicultural treatments most appropriate to meet the objectives of the landowner. Silviculture is to forestry as agronomy is to agriculture, in that it is concerned with the technology of growing vegetation. Like the rest of forestry itself, silviculture is an applied science that rests on the more fundamental natural and social sciences. The immediate foundation of silviculture in the natural sciences is **silvics**, which deals with the growth and development of single trees and other forest species as well as whole forest ecosystems. Among the sources of information about silvics is a very long legacy of books upon which silviculture is based by: Daniel, Helms, and Baker, 1979; Spurr and Barnes, 1980; Kimmins, 1987; Burns and Honkala, 1990; Oldeman, 1990; Whitmore, 1990; Kozlowski, Kramer, and Pallardy, 1991; Lassoie and Hinkley, 1991; Packham, *et al*., 1992; Barnes *et al*., 1998; Kimmins, 2003; Waring and Running, 2007; and Perry, Oren and Hart, 2008.

The competent practice of silviculture, whether it be crude or elaborate, demands that a forester acquire as much knowledge as possible of ecology and all its subdisciplinary areas (e.g., population, community, ecosystem), as well as fields such as plant physiology and morphology, entomology and pathology, biogeochemistry, hydrology, biometeorology, and soil science. It is also through silviculture that a major part of the growing store of knowledge about trees and forests is applied. In addition, it is essential to understand the fundamentals of individual human community and society behaviors, their cultural and religious values, and their economics, if silviculture is to achieve the goals and objectives of managing forests, woodlands, and trees successfully. This knowledge is not learned once for a lifetime. The forestry practitioner must keep abreast of new information and ideas through communication with other members of the profession and maintain familiarity with the results of research. Silviculture can therefore be considered a sub-discipline that is at the very heart of training a forestry professional (Fig. 2.1).

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

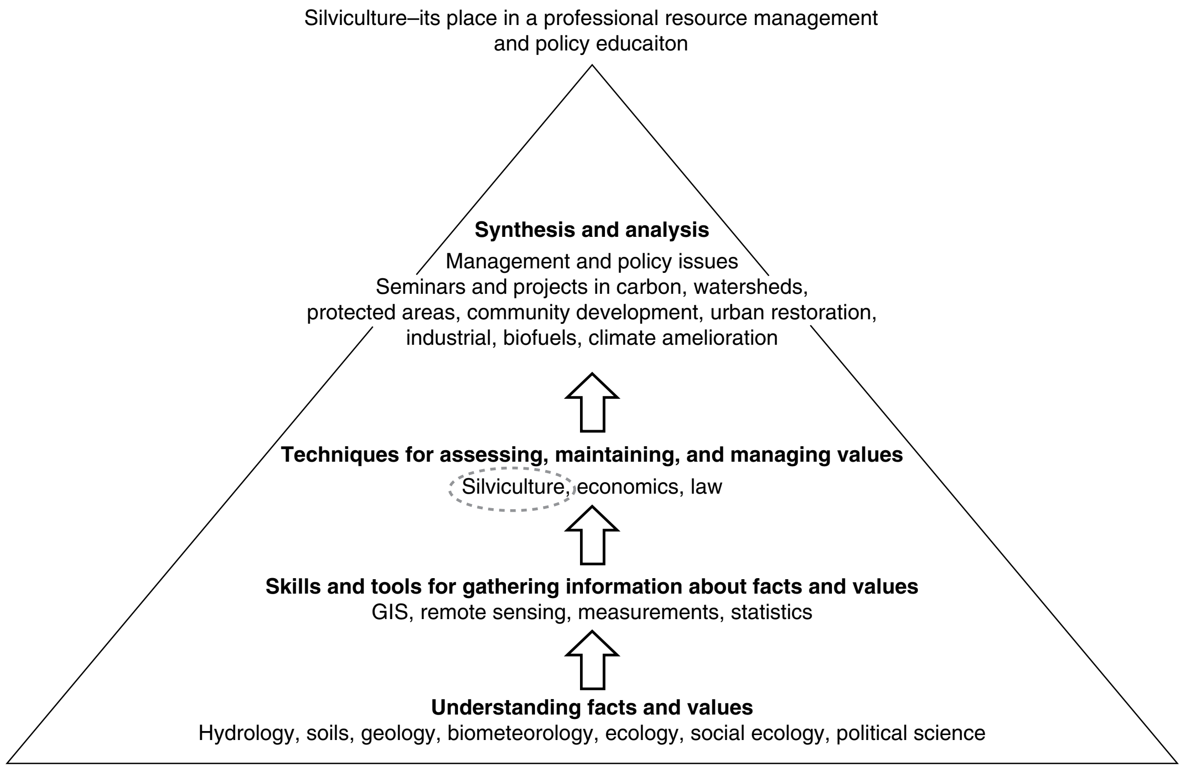

Figure 2.1 A graphical depiction of where the subject lies within the multi-disciplinary training of a professional forester. *Source:* Mark S. Ashton.

Although formal research is indispensable, it does not lead to total knowledge, nor does it relieve the forester of responsibility for additional thought and continual observations in the forest. In applied sciences, such as silviculture, in the absence of total knowledge we are always condemned to act on the basis of thoughtful judgment. Skillful practice itself is a continuing, informal kind of research in which understanding is sought, new ideas are applied, and old ideas are tested for validity. The observant forester will find answers to many silvicultural questions in the woods by examining the results of earlier treatments of the forest and accidents of nature. This component of silviculture can be considered the art of silviculture and is based on the forester's inherent adaptive learning experience, intuition and understanding of the science, keen sense of observation about the natural world, and ability to understand human behaviors and desires as well as translate this understanding into practice. The forester is a naturalist in the broadest sense of the word, and every forester should strive for these attributes.

The Purpose of Implementing Silviculture

Silviculture is designed to create and maintain the kind of forest that will best fulfill the objectives of the owner and the governing society. The production of timber, though a common objective, is neither the only nor necessarily the dominant aim in silviculture. Frequently, especially with public forests and private non-industrial forests, benefits such as recreation or aesthetics may be more important, and water and wildlife always have to be taken into account.

Most silvicultural practices are applied in the course of timber harvesting because the value of the wood removed greatly reduces the cost of the operations. It is through the manipulation of growing space by removing trees that much of the other values such as improving wildlife habitat, creating vistas, or encouraging a vigorous groundstory for surface watershed protection can be achieved. This is true even if timber production is only a secondary or tertiary objective of management. Silviculture for the cultivation of both wood and non-wood products (fruits, fiber, resins) is also the most intricate kind because the species and quality of trees are of greater concern than they would be with other forest uses. Designing silviculture for wildlife management is also complicated, but mainly because of the difficulty of determining the kinds of vegetation that mobile and elusive animal populations require. Once the kind of required habitat is selected, the silviculture is not difficult to design.

Some of the biggest problems in silviculture include getting owners and society to define their management objectives and, especially, the degree of priority attached to various uses. It is the responsibility of foresters to work out the details, which include the design and implementation of silvicultural treatments, but owners, the

public, and legislative bodies must determine the actual policies about allocations. Management cannot continue if the difficult and often argumentative decision making is left to single-minded user groups. Even worse problems can be caused by amateur prescription of silvicultural practice through simplistic rules ordained by legislatures, courts, or accountants.

Resource Issues Applicable to the Use of Silviculture

Resource issues are extremely varied given the enormously wide social and economic circumstances within which forests and woodlands can be found. Forests are: used for subsistence living in remote regions; irresponsibly cleared for unsustainable agricultural projects (and thus threatened with destruction and degradation); managed for intensive industrial use; conserved as wildlife habitat; maintained as a source of drinking water for downstream cities; and developed for open-space recreation and city parklands. Important resource values are listed below by the products and services that trees and forests provide and for which silviculture is directly applicable.

Products

1) Biomass and wood fuel. Two-thirds of people in the world, mostly from developing nations, are still dependent upon fuelwood or charcoal for cooking and heating. Now coming full circle, modern technologies are being developed to use biomass, primarily from fast-growing biomass plantations, but also a secondary product from other forest harvest operations, as an energy source in developed nations.
2) Fiber. Paper, ropes, and other fiber products were predicted at the start of the computer age to dramatically decrease in use. Instead they have significantly increased and are projected to continue to do so. Though recycled paper products have become much more common, even recycled paper requires replenishment with virgin fiber.
3) Composite materials. Over the last 50 years, technology has developed a variety of composite wood products (plywood, particle board, and oriented-strand board) that are cheaper substitutes for dimensional sawtimbers and that are derived from what was once considered waste. Such materials are now widely used. More recently, wood–plastic composites have been developed for a range of uses that were formerly restricted to plastics, ranging from shoes to the bodies and interiors of cars, planes, and boats.
4) Dimensional construction and support timbers. Worldwide, demand for timber products for building construction will continue to increase. Timber products are one of the most carbon-neutral and energy-efficient products. These timbers are increasingly coming from intensively managed plantations (e.g., Douglas-fir, *Eucalyptus* spp., loblolly pine, and radiata pine).
5) Luxury timbers and veneers. High-value woods used for furniture, artisanal products, musical instruments, flooring, paneling, and building interiors will always be demanded by society. These timbers continue to come from native forests, and are increasingly from second-growth origin. Plantations of luxury timber are rare (e.g., teak), because of their time to reach maturity.
6) Tree fruit and nut crops. Cultivation of fruit and nut trees requires silviculture treatments in native forests, mixed tree gardens, and orchard plantings. Such treatments focus on the condition of individual tree crowns to maximize nut and fruit productivity.
7) Tree resins, oils, and saps (e.g., rubber, maple syrup, turpentine). Trees managed to produce resins, saps, and oils from the stem need specific silvicultural treatments for both native forests and for their cultivation in plantations.
8) Lianas and vines. Many products (rattan, basketry, medicinals, cordage, vegetables) are garnered from vines. However, vines and lianas require trees and shrubs for support and stages of successional habitat that silviculture can provide.
9) Understory plants. Understory plant crops (e.g., spices, medicinals, coffee, cacao) of forests, plantations, and agroforestry systems require shade and soil-fertility conditions that trees can provide.

Services

1) Supplying clean water. The cleanest water comes from forested watersheds that act to filter and/or sequester pathogens and pollutants from water and air. Many urban areas are focused on acquiring and protecting upstream land from development in order to manage it as forest for drinking water supplies to reservoirs.
2) Stormwater mitigation. At a regional scale, forested swamps and floodplains are usually the frontline for mitigating stormwater and flooding events and controlling shoreline erosion caused by typhoons and storms. In addition, wetlands, swamplands, and forests can control and regulate seasonal meltwaters and monsoon or rainy season floods. At a more local scale, trees and woodlands within cities can mitigate local stormwater runoff, reducing downstream pollution and excessive discharge. At both scales, silviculture is needed to actively reforest and create the optimum conditions for mitigation.
3) Carbon sequestration. Since the 1990s, the focus in reducing atmospheric greenhouse gases has shifted towards natural carbon sequestration by forests and trees, which depends on minimized deforestation, reforestation, and management practices that delay harvesting and increase growth.
4) Urban climate and environmental mitigation. Within cities and towns, trees and woodlands can be planted

and cultivated to locally reduce glare, sound, temperatures, and winds.

5) Open-space recreation. Silviculture can be used to create vistas, screens, and recreational trails for biking, hiking, and skiing.
6) Wildlife habitat. Forests and woodlands provide critical habitat for all sorts of wildlife. Particularly important to some societies are the opportunities to hunt game animals, and mandates to conserve endangered species. Silviculture can be used to both create the habitat and maintain it through manipulating forest structure, composition, and site.
7) Forest health and restoration. Silviculture can be applied for: (a) controlling invasive plants, insects, and diseases; (b) regulating and controlling fires; (c) restoring and conserving biodiversity; and (d) stabilizing and protecting fragile landscapes.

The products and services listed can often be produced together in a stand within the forest, plantation, or agroforestry system. In other circumstances they are incompatible and have to be managed separately. Different regions of the world, and even within the same region, have very different sets of priorities and values because of social, economic, and biological circumstance.

Scope and Terminology of Silvicultural Practice

Silvicultural practice encompasses all treatments applied to forest and woodland vegetation and their sites. Although there is much more to the understanding of these treatments than their definitions and nomenclature, the terminology must be understood and used carefully and precisely. **Sloppy use of the terms causes all manner of misunderstanding within the forestry profession and in dealings with the general public. For example, some foresters categorize all cutting as either "clearcutting" or "selective cutting." This not only stunts the development of their own understanding of forestry practice and causes blunders, but also generates continued confusion.** The terminology in this book generally adheres to that promulgated by the Society of American Foresters Silviculture Instructors Sub-Group (1994) and the Commonwealth Forestry Bureau (Ford-Robertson, 1978). It departs only where further improvement in clarity or precision seems imperative.

Silviculture should be governed by several guiding principles. The first two are of the greatest importance, dealing with the imitation of nature and the conservation of site productivity. The other four principles are to be used as reminders to forest practitioners by serving as a check for potential unintended consequences of poor silviculture judgment. The following is a brief description of each of the six principles.

Principle 1: Imitating Nature Through Silviculture

The most magnificent forests that are ever likely to develop were present before the dawn of civilization and grew without human assistance. It is therefore wise to recognize that nature's forests and woodlands are the result of millions of years of exposure to risks of climate, disease, pestilence, and disturbance. Therefore, dramatic silvicultural deviations in species composition, successional process, and stocking can often have detrimental consequences. Human purpose is introduced by preference for certain tree species, stand structures, or processes of stand development that have desirable products and/or services. Where fine forests have developed in nature, they are usually found to have been the result of disturbances followed by long periods of growth. In silviculture, natural processes are deliberately guided to produce forests that are more useful than those of nature, and to do so in less time. Silviculture is therefore an anthropocentric discipline guided by ecological constraints. Whatever society or individuals demand of a forest, whether utilization or preservation, with active or passive management approaches, those decisions are human ones, and they all have immediate consequences and future impacts on a forest that should be recognized.

Principle 2: Conservation of Site Productivity

Paramount among the objectives of forestry in general and of silviculture in particular is the maintenance of the productivity of the living forest. The site is the total combination of the factors, living and inanimate, of a place that determines this productivity. The site factors that are most subject to long-lasting harm are those of the soil, which is one of the least renewable resources used in silviculture (see Chapter 5).

Forests are usually the result rather than the cause of geographical precipitation patterns, though recent evidence is suggesting that forests that are large enough most definitely mitigate climate change and can promote processes of local precipitation such as convectional thunderstorms. However, the basic supply of solar energy is the most vital site factor and is beyond silvicultural control. Silviculture therefore rests heavily on manipulation of the microclimate of a site. Its effects on the macroclimate are limited to those caused by photosynthetic removal of carbon dioxide from the atmosphere and by transpiration of humidity into it.

The living organisms of a place are site factors themselves. However, they can reproduce themselves and are thus the epitome of the renewable resource. If none are rendered extinct, damage to these living components of the site is not likely to be permanent, even though it can be

serious and long-lasting. There are always uncertainties over the extent to which silviculture should discriminate against "undesirable" forms of life.

The most obvious and least repairable kind of damage to the soil is physical erosion. Careless treatment, especially when associated with roads and trails used for timber extraction, can cause accelerated erosion that may negate the soil formation processes of a thousand years. A more subtle kind of chemical erosion can result if the remarkable capacity of forest vegetation to recycle nutrients in place is so impaired that large amounts of vital chemicals are lost to surface runoff or leaching. These two kinds of erosion cause double harm because they reduce not only the productivity of the soil but also the quality of the water that flows from it. Soil damage impairs the capacity of the site to yield all of the primary tangible benefits of the forests – vegetation, animal forage, and good water.

It is entirely possible to conduct forestry permanently without the degradation that is almost inevitable in most agriculture and in other "higher" uses of land. However, realization of this potentiality is not automatic. The productivity of the managed forest as a whole is improved through attainment of the four guiding principles described in the next few sections.

Principle 3: Control of Stand Structure and Process

Silviculture is a kind of process engineering or forest architecture aimed at creating structures or developmental sequences that will serve the intended purposes, be in harmony with the environment, and withstand the burdens imposed by environmental influences. Because stands grow and change with time, their design is more sophisticated and difficult to envision than that of static buildings. Furthermore, stands alter their own environment enough that the forester is partly creating a new ecosystem and partly adapting to the one that already exists.

As will be described in more detail in Chapter 4, the possible variations in stand structure and process are almost infinite. The shapes and sizes of stands can be altered for many purposes. Among these are controlling silvicultural treatments and harvesting, creating attractive scenery, altering animal habitat or controlling pest populations, trapping snow, and reducing wind damage. The shapes of stands should be fitted to the patterns usually already found in nature that are dictated by soils and terrain. While the arrangement of stands in checkerboard patterns has a certain administrative appeal, the natural characteristics of land are not, and should generally not be arranged in ways that conflict with the topography of the land.

The internal structure of a stand is determined by considerations such as variation in species and age classes, the arrangement of different layers or stories of vegetation (usually differing as to species), and the distribution of diameter classes. Much of this book is concerned with the purpose and means of achieving these kinds of variations in structure and developmental process.

Principle 4: Control of Composition

One important objective of silviculture is to restrict the composition of stands to what is most suitable to the location from economic and biological standpoints. This frequently means that the total number of species in a managed stand or forest is less than that of the natural forest at that site.

Species composition can be controlled basically by regulating the kind and degree of disturbance during periods when new stands are being established. In this way, environmental conditions can be adjusted to favor desirable vegetation and exclude undesirable species. Regulation of the regeneration process by itself is not always sufficient to provide adequate control over stand composition. It is often necessary to supplement this approach by removing the undesirable vegetation during or after periods of stand establishment. Cutting, poisoning, controlled burning, or regulated herbivorous browsing may be used to restrict the competition and regeneration capacity of undesirable vegetation.

Desirable species and genotypes can be favored in a more positive way by planting or artificial seeding. In some circumstances it is also possible to improve on nature through the introduction of species that do not occur in the native vegetation (e.g., timber and fruit trees; nurse trees in agroforestry), provided that they are adequately adapted to the environment and do not become invasive.

Principle 5: Control of Stand Density

Managed forests are often too densely or too sparsely stocked with trees. This is subjective based upon what human values are being managed for. If stand density is too low, the trees may be too branchy or otherwise malformed, and the unoccupied spaces are likely to be filled with unwanted vegetation in wetter climates. This condition arises from failure of natural regeneration or establishment of planted seedlings. This phenomenon of unoccupied growing space is therefore most common in the early life of a stand, but its consequences may linger after the surviving trees have grown to occupy all of the space available. Excessively high stand density causes the production to be distributed over so many individual trees that none grow at an optimum rate and too many decline in vigor. Unless stand density is controlled at the time a stand is established or during its development, it is almost sure to depart from optimum density for growth at some stage of its life.

Without proper management, many areas of land potentially suited to growth of forests tend to remain unstocked with trees (Fig. 2.2). Legacies of past land abuse (fires, destructive logging, grazing, agricultural

(a)

(b)

Figure 2.2 Much of silviculture has always consisted of rehabilitation efforts and of knowing what will happen as a result of treatments of the forest. This sequence of pictures from 1938, 1949, and 1969 shows a planted stand at a National Forest in northern Idaho, in three stages of development. The tract had been cut-over from a logging railroad in 1930–1931 and was both burned and acquired just before the first picture **(a)** was taken. Planting of western white pine and Engelmann spruce was done in 1939 and 1940. The subsequent pictures **(b** and **c)** show the development to age 30, of the mixture of planted trees and other conifers that seeded-in naturally. *Source:* **(a–c)** US Forest Service.

(Continued)

(c)

Figure 2.2 (Continued)

clearances, and other kinds of forest devastation) have already created many large open areas that can be reforested only by planting. In many regions, **restocking** of deforested areas can be considered a common silvicultural goal.

In many stands, severe losses are caused by damaging agencies such as insects, fungi, fire, and wind. Substantial increases in merchantable production may be achieved merely by salvaging material that might otherwise be lost, but this decision needs to be considered carefully. Jumping into action too quickly to salvage forests sometimes can further exacerbate such issues by causing severe erosion or facilitating further spread of insect or disease. Protection from damaging agencies can result in further increases in production. Forest protection often involves modification of silvicultural techniques. Those areas set aside for wilderness, scenery, or scientific study clearly require protection. Sound policies about the stewardship and use of these preserves inevitably involve something other than leaving them absolutely alone.

Principle 6: Control of Rotation Length

Stands of trees are not immortal. In most commercial situations, there is an optimum size or age to which trees should be grown. The period of years required to grow a stand to the desired condition of either economic or natural maturity is known as the **rotation**. Controlled reductions of stand density or such measures as fertilization and drainage can shorten rotations by making the final-harvest trees grow to the desired sizes at earlier ages. Trees in commercial circumstances allowed to grow beyond the optimum size do not continue to increase in value at rates sufficient to provide an acceptable return on either the costs of growing them or the investment represented by their own value. The risk of decay or other damage may increase the possibility that the trees will decline in value, be lost, or become a hazard. The reservation of overmature trees or even of dead trees is now the norm to maintain some element of structural diversity even within the most intensively managed forests. This is to benefit some wildlife species, microbiota, or simply for scenery or cultural legacies. Increased sequestration and storage of carbon can also be a financial incentive to lengthen rotations in many commercially managed forests.

In the virgin forest, large timber, like gold in the hills, is usually first exploited. The greater the amount extracted, the more difficult and expensive it becomes to find and extract more. It can be extremely difficult to correct the impacts of exploitation in forests that are intended to be sustainably managed for products (timber or non-timber). In fact, many are simply converted to other forms of land use because their commercial timber value has been

so depleted. In a managed forest, the growth of stands can be planned so that any use of them is on a more efficient, economical, and predictable basis. It helps to create good stands that are so located that the cost of transporting timber from them is kept under control. Planned reductions in the number of trees on an area not only makes them reach merchantable size more quickly but also leaves more space between trees for extraction of logs during partial cutting.

The Silviculture Framework for Managing a Forest

This section provides a conceptual framework for thinking about how silviculture should be implemented using the guiding principles that are listed and described in the preceding section. Taken together, this provides the forester a guide upon which to develop a silvicultural set of treatments for the unique biophysical and social circumstance that they face. The set of treatments devised by the forester is defined as a **silvicultural system**. The framework should be based upon the ecological and social knowledge and experiences of the forester. The system devised is by no means taken as a general recipe equivalent to a "cook book." Unfortunately too many of these "recipes" exist in forestry and land management.

Defining the Spatial Scale of Management: The Stand and the Forest

A **stand** is a contiguous group of trees sufficiently uniform in species composition, arrangement of age classes, site quality, and condition to be a distinguishable unit. It is the basic and usually the most refined management unit upon which silvicultural treatments can be applied. The internal structure of stands varies mainly with respect to the degree that different species and age classes are intermingled. The simplest kind of structure and developmental pattern is that of the pure, even-aged plantation. The range of complexity can extend to a wide variety of combinations of age classes and species in various vertical and horizontal arrangements. The development of stands over time, or **stand dynamics**, is considered in Chapter 4.

From the standpoint of forest management, the term "forest" has a special meaning and denotes a collection of stands administered as an integrated unit, usually under one ownership. Putting stands together into forests is especially important in regulating harvests of products (timber and non-timber), as well as managing wildlife populations and large watersheds.

One objective of this type of planning for timber is to achieve a sustained yield of products. The forest, not the stand, is the unit from which sustained yield is sought. Management studies of prospective growth and yield determine the volumes of the products to be removed from the whole forest in a given period. The silvicultural principles listed earlier should govern the sequence and manner in which individual stands reproduce the required structures, yields and compositions. The tendency to treat large groups of dissimilar stands as if they conformed to a uniform, hypothetical average should be studiously avoided. However, a decision must be made regarding the minimum size of stand delineation.

Silviculture that is concerned with natural processes involving wildlife, flowing water, and whole landscapes also involves the arrangement and juxtaposition of stands. Differences between adjacent stands and the distribution of stands across landscapes need to be taken into account as part of the management of forests or ecosystems at much larger landscape, watershed, and regional scales.

The size and number of stands recognized depend on the intensity of practice, the economic values and social drivers of the stands, the diversity of site conditions, and the ease of mapping. Where intensive forestry is feasible, stands as small as 0.6 acres (0.25 ha) may be recognized. But under crude, extensive practice, the same forest might be divided into units no smaller than several hundred acres. The best policy is to recognize the smallest stands that can be conveniently delineated on the maps of forest types and age classes used in administration. Even after stand maps have been put on paper, the forester must still deal with variations that actually exist within each stand. From a technical perspective, each portion is best treated separately, although acceptance of too many variations would eventually create a mosaic of conditions that would be awkward for most operations. With remotely sensed data that can be obtained to the nearest 10 ft^2 (1 m^2), technologies make the identification and delineation of stands almost a continuous process as forests change and develop over time. This makes silviculture and its associated treatments more harmonious with the continuums and gradients of ongoing natural processes.

The production of benefits by forest stands is controlled by the stand developmental processes, whether these benefits be wood, wildlife, water, forage, or scenery. The processes start with the birth of the stands, continue with competition between trees, and end with the death of old trees and their replacement. The simplest kind of stand development process is that of the **pure even-aged stand** in which the trees are "pure," that is, all of one species, and start together after the previous stand is removed. Such stands are often ones that have been planted. **Uneven-aged stands** (two to three age classes are considered **multi-aged**; more than three age classes are considered **all-aged**) have trees or (more commonly, groups of trees) of different ages and

much more complicated developmental patterns. **Mixed stands** have more than one tree species, and the interaction between them makes their development even more complicated, especially if they also have more than a single age class of trees. The development of these different kinds of stands is discussed in Chapters 4 and 5 and Chapters 8–13.

Defining Kinds of Silvicultural Treatments

The act of replacing old trees, either naturally or artificially, is called **regeneration** or **reproduction**. These two words, which are synonymous in this usage, also refer to the new growth that develops.

There is also the question of the terminology used for silvicultural treatments. There are two broad categories: (1) **methods of reproduction** refer to treatments of stand and site during the period of regeneration or establishment, while (2) **tending** or **intermediate cutting** refers to post-establishment treatments that occur at other times during the rotation (Fig. 2.3).

Reproduction or **regeneration cuttings** are made with the twin purposes of removing the old trees and creating environments favorable for establishment of regeneration. The period over which such regeneration treatments extend is the **reproduction** or **regeneration period**. Regeneration cuttings range from one to several in number, and the regeneration period may extend from several years to several decades. In truly uneven-aged stands, regeneration is almost always underway in some part of the stand. The regeneration period begins when preparatory site and cutting treatments start, and it ends when young trees, free to grow, are dependably established in acceptable numbers. The **rotation** is the period during which a single crop or generation is allowed to grow.

The names of the various methods of regeneration (see Chapter 6) are primarily defined by regeneration origin and secondly by the patterns of cutting in time and space that determine the structure of the new stands created. They distinguish between reliance on reproduction from seeds or reproduction from vegetative sprouts and may tell a little about the degree of shading of new seedlings. Later chapters describe how clearcutting is associated with pure, shade-intolerant even-aged stands (Chapter 8); seed trees with a dependence on a nearby seed source (Chapter 9); shelterwood methods and their uneven-aged (multi-aged) variants, with advance regeneration (Chapters 10 and 11); coppice methods, with sprout regeneration (Chapter 12); and the selection system, with uneven-aged (all-aged) stands (Chapter 13). The names of the methods, systems, and kinds of stands usually only begin to describe fully the details of silvicultural management programs.

Silvicultural treatments are not limited to ensuring regeneration. Other treatments may be applied after the stand is established and during the long period that elapses while the stand grows through various stages until it is ready for replacement. Various **intermediate cuttings** or **tending operations** are conducted to improve the existing stand, regulate its growth, create particular structure, treat individual trees, and/or provide for early financial returns, without any effort directed at regeneration. Sometimes these treatments are referred to as **stand improvement operations** or **timber stand improvement (TSI)**, when they yield no products or services (Chapters 19 and 22).

Intermediate cuttings that are aimed primarily at controlling the growth of stands by adjusting stand density or species composition are called **thinnings** (Chapters 21 and 22). Treatments conducted to regulate species

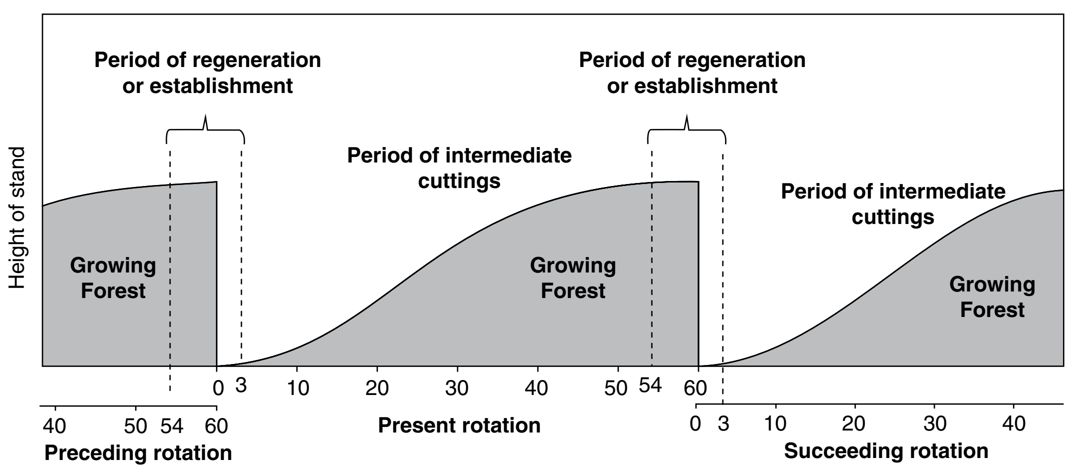

Figure 2.3 The relationship between the period of regeneration and the period of intermediate cuttings is shown for a sequence of even-aged stands managed on a 60-year rotation according to the shelterwood system. In this system the new stand is started before the older one is completely removed. *Source:* Yale School of Forestry and Environmental Studies/Mark S. Ashton.

composition and improve very young stands are **release operations** (Chapter 20). Those that involve only the branches are **pruning** (Chapter 19). Many kinds of intermediate cutting or tending can now be accomplished without actually cutting down trees, for example, by girdling and use of herbicides.

Protection against injury is as much a part of silviculture as harvesting, regenerating, and tending of forests. It is so important that it has led to fields of specialization in forestry such as restoration ecology, entomology, pathology, control of invasives, and fire control, and now impacts of climate change. Chapters 25, 26, and 27 are devoted to outlining the silvicultural aspects of these fields. The details of almost any successful silvicultural system include significant modifications designed to reduce injuries. Where such measures fail or are inadequate it is sometimes desirable to conduct **salvage cuttings** to recover the values represented by damaged trees or stands.

A program for the treatment of a stand during a whole rotation is called a **silvicultural system**. The silvicultural system is usually given the same name as the regeneration method that is used during stand replacement. This is because these regeneration methods determine the kinds of stands and stand developmental processes that occur during a whole rotation.

Role of Cutting in Silviculture

The techniques of silviculture proceed on the basic assumption that the vegetation on any site tends to extend itself aggressively to occupy the available growing space. The limit on growing space is usually set by the availability of light, water, inorganic nutrients, or carbon dioxide. Generally, the most limiting of these factors will determine the available amount of growing space, although an abundant supply of one factor can partially offset deficiency of another. If the vegetation nearly fills the growing space, the only way that the forest can be altered or controlled is by removing trees and other plants to open up growing space. In reproduction cutting, this is done to provide room for the establishment of new trees; in intermediate cutting, it is done to promote the growth of desirable trees already in existence. Paradoxical as it may seem, useful forests are created and maintained chiefly by judiciously choosing and destroying some of their parts. One of the characteristics of life is death; if there were no death, there would be no space for new life. Simply put, silviculture usurps nature's role by creating new trees rather than waiting for disturbance and by facilitating the survival of chosen existing trees by intentional thinning rather than natural self-thinning.

The ax and other means of killing trees can, in other words, be used for the construction as well as the destruction of the forest. What is left or what replaces what is harvested is more important silviculturally than what is cut. Unfortunately, much of the general public as well as some loggers have eyes only for what is cut and regard the harvests as simply the mining of a non-renewable resource.

Preoccupation with the trees should not cause foresters to overlook the lesser vegetation and the animals that are a part of the forest community. The animals ultimately depend on the vegetation for food and thus do not compete directly for the growing space. However, whether they be defoliating insects or carnivores that feed on herbivorous mammals, they exert major influence on the nature of the vegetation even as they are, in turn, controlled by it. The fauna and non-woody vegetation of the forest are as affected by cutting as the trees are.

Effect of Cutting on Growing Stock

Cutting trees controls not only the composition and structure of forest stands, but also the relationship between trees reserved for continued growth and the space created for new trees. It is therefore important to understand the long-term, cumulative effect of cutting operations in building or degrading a forest.

The trees that must be reserved somewhere in the forest to continue production are the **growing stock** or **forest capital**. The volume of wood that is grown in the future depends on the quantity and condition of growing stock that is maintained. Cuttings regulate the amount of this growing stock and its distribution within individual stands or among the various stands that comprise the forest. The regulation of growing stock is of most crucial importance in silviculture when partial cuttings are applied within stands.

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Part 2

Ecological Foundations of Silviculture

The ecological foundations for silvicultural practice through understanding the complexities of site and scale; the development and dynamics of forest stands; and the nature of forest regeneration in relation to disturbance.

3

Ecological Site Classification, Stands as Management Units, and Landscape-Scale Planning

Introduction

The Ecosystem Concept

It was recognized long ago that both study and application of ecology suffered from excessive compartmentalization. The total flora of interacting forest plants is far more than just trees; the total biota of a place includes not only plants but all the orders of the animal kingdom that are present. An ecosystem, however, is more than just the living organisms. It also includes the non-living physical and chemical factors that interact with the living organisms (Tansley, 1935).

In applying silvicultural treatments, a forester is, in some degree, manipulating many sizes of ecosystems simultaneously (Reichle, 1981; Perry, Oren, and Hart, 2008). At one extreme are the world cycles of carbon, oxygen, and water; the microenvironment around a pine seedling in the shade of a log is at another; and in between are the cycles of mineral nutrients and the combination of different kinds of forest stands on a hillside. **Forest ecosystem management** includes the design and application of silvicultural solutions that are based on analysis of all the ecological factors known to operate in the system involved. In other words, silviculture has always been ecosystem management, provided that it is conducted on the basis of such analysis. Ecosystem management is one of the keys to maintaining biodiversity for it requires consideration of the interaction and habitat requirements of all living organisms.

Silvicultural treatments achieve their results through deliberate manipulation of the forces represented by physical, chemical, and biological processes that alter ecosystems in somewhat the same manner that purely natural forces produce changes in ecosystems. In ecosystem management, it is necessary to consider the spatial arrangement of stands of differing ages and species composition and how they vary within an ecological site condition. In other words, it is best if silvicultural planning and forest management are not restrained by boundaries of stands and ownerships. Insofar as possible, such planning should consider the landscape scale in which ecosystem boundaries are defined by watersheds, climate, topography, and the ranges of plant and animal species.

All good ideas survive to be overdone, and the ecosystem concept is no exception. It is too easily translated into the philosophically attractive concept that each biotic community is a superorganism in which each constituent species is indispensable and somehow depends on every other species. Although it can perhaps be said that every part of an ecosystem has some effect, even if minuscule, on every other part, each part does not depend on every other part. There are many important interactions between particular species, such as symbiosis and competition, predation and parasitism, or simply shading of one plant species by another. Although these interactions need to be recognized (and used) in silviculture, they do not mean that all parts are like essential cogs in a whole engine. The vast majority of species are adaptable to many different conditions and often move around independently of their associates. If two different species are dependent on each other, they are usually adapted to move or respond to change together.

Natural disturbances and subsequent development processes commonly lead to the development of particular combinations of species of trees, lesser plants, animals, and other forms of life on particular kinds of sites in a given climatic region. These are called **communities**. Some species within them are dependent on others. For example, pines depend on mycorrhizal species of fungi; herbivores, on the foliage; and bark beetles, on dead or dying trees. However, most of the trees and other organisms are not dependent on each other, and the weight of evidence is against the idea that they have, as is often claimed, lived in association and been dependent on each other for millions of years.

Evidence from pollen deposits shows that most tree species have moved around quite independently of each other since the continental glaciers started to shrink about 15,000 years ago. Most modern plant communities, including those in the tropics, are less than 8000 years

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old and have responded to climatic changes that have taken place even more recently (Davis, 1983; Delcourt and Delcourt, 1987; Hunter, Jacobson, and Webb, 1988).

There does, therefore, seem to be some entirely natural precedent for silvicultural changes in species composition of forest ecosystems. However, this does not mean that all changes, subtractions, or additions are safe or desirable. Changes should be made only in the light of the best knowledge available about relevant mutual relationships between species in natural forests of a locality. Foresters who deal with any managed forests should always watch for undesirable (and desirable) consequences of departures from more natural conditions and be ready to act on the knowledge.

In considering silvicultural manipulations of ecosystems, it should be recognized that the same degree of "naturalness" cannot be maintained in all forests. Not all silviculture should mimic the old-growth stage of development, even if there was enough freedom from disturbance to allow it. Just as there are variations in intensity of silvicultural practice, so should there be variations in "naturalness." It is also necessary to recognize that most forests situated where silvicultural management is feasible are already significantly modified by human action (Whitney, 1996), so it may be virtually impossible to return to a pure state of nature.

Natural preserves should be extensive enough to maintain all native species and represent all natural habitats; it is not enough to confine them to forests, such as wilderness areas that are merely difficult of access. Many stands from which wood is harvested can be expected to maintain most of the biodiversity of an area if appropriate attention is given to the relative dominance of species and the characteristics of silvicultural disturbances. Intensively managed forests, such as plantations, do not necessarily maintain a high degree of natural diversity; however, even these maintain most of the basic ecosystem equilibria, such as high biological productivity, uptake of carbon dioxide, retention of nutrients, control of erosion, and regulation of hydrologic processes.

This chapter systematically describes the ways foresters should first interpret the differences in forest vegetation and in the variations of soil and environment across a landscape. These interpretations create the basic planning units upon which to apply silvicultural treatments. This process and its end products include an understanding of: (1) ecological site classification; (2) stands and stand maps as the basic management units in silviculture; and (3) protocols for integrated landscape-level assessments and planning. They can be considered the basic building blocks for any vegetation management of a forest, woodland, or natural resource landscape, whether in a wildland area, an agricultural landscape, or in an urban environment. This chapter first provides a rationale for identifying and classifying sites and then describes the different methods of developing a site classification, either indirectly through measures of tree height (site indices) or plant indicators, or directly through soil analysis and measures of landform. Ecological site classifications are conveyed through case study examples. This chapter then describes the protocol for defining the spatial and temporal scale of stands as the basic management units of silviculture. Stands are usually defined within a site classification system, and are identified by similarity in age-class distributions, species composition, and stocking densities of vegetation. Finally, a rationale and protocol for landscape- and regional-scale planning are provided using ecological guides and benchmarks based on an understanding of natural forest disturbance regimes.

Ecological Methods of Identifying and Classifying Sites

One of the ideals of silviculture is to place the right tree in the right place with just the right amount of growing space at each stage of development. Questions about what is right usually involve much opinion and analytical thought about ecology and social objectives. One extreme view is that the vegetation composing a stand should consist of those species and genotypes best adapted to survive and reproduce on the site as a result of many generations of natural selection. However, the attributes that provide for survival of the species are not necessarily those that meet the requirements of people and societies. The natural composition is, furthermore, neither static nor well defined; it is instead dynamic and subject to continual changes resulting from developmental processes initiated by competition or natural disturbance. This means that even if one adheres to the natural composition ideal, a choice must still be made about which developmental stage or developmental pathway to imitate. Another problem with this approach is that human disruptions have made it very difficult to know what natural compositions might have existed in many locales.

At the other extreme is the view that silvicultural engineering can make people's desires for a particular species composition come true, as is the case with much of modern-day agriculture. This is the idea of modifying the site to fit the crop or plant selected. However, problems such as getting trees to survive through dormant seasons cause foresters to stop short of fully imitating the intensive agriculture of arable annual crops. One may move maize from Central America to Minnesota, but the same cannot be done with Honduran mahogany. In fact, one cannot safely move trembling aspen from a moist site to a dry one within a Minnesota farm woodlot.

Because neither natural factors nor human wants can be ignored, the most logical courses lie between these extremes and also vary with the circumstance. The first step in this course setting is to determine the limitations imposed by the environmental factors that collectively constitute the site. This restricts the number of species to be considered in the second step, which is to choose the species (plural or singular) that will most nearly meet the social and ecological objectives of stand management. A third step is consideration of the degree of artificial control that will be exerted over the genetic constitution of selected species. This may range from simply accepting the existing genetic makeup of a species to using intensive breeding methods in order to develop more desirable genotypes.

The basic objective is to use genetic material that will not only survive and thrive on the site but also yield the wood, fiber, biomass, or some other environmental benefit (e.g., fruits, medicinals, resins, aesthetics) at some optimum rate. However, it should be noted that suitable "genetic material" is seldom any single genotype. Even if only a single species is to be used, it is best to maintain some degree of genetic variation within each stand with multiple genotypes. A better choice may also be a combination of many species in mixture.

Nature of Site or Habitat

Anything that is done in silviculture should be based on knowledge of the capacities and limitations of the site or habitat in which the trees are to be grown. Although the term **site** is the traditional one denoting the total environment of a place, **habitat** more fully denotes the idea that the place is one in which trees and other living organisms exist and interact. As far as trees and other plants are concerned, the site is controlled mainly by the total physiologically available supply of light, water, carbon dioxide, and various nutrients. The primary driving forces that control these supplies are the input of solar radiation and precipitation, which together define the climate of a region. Total annual levels of radiation and precipitation are important, but growing conditions are also affected by seasonality throughout the year, producing wet and dry seasons and summer and winter.

Solar radiation is controlled largely by latitude, and so it varies on a regional scale. It sets the absolute limits on the productivity of a site, both as the energy input for photosynthesis, and more generally in controlling the temperature range in which organisms must function. Precipitation levels vary in more complex patterns largely associated with the movement of humid air from oceans onto land masses. The balance between temperature and precipitation strongly affects plant survival and productivity. Much greater precipitation is required in Florida than in Ontario to support forest growth, because of the greater potential for evaporation from both soils and leaf surfaces in the hotter region.

For a particular location on the landscape, the effect of climate is modified by the landform, which is the nature of the surficial geological material plus topography. Landform characteristics influence the amount of solar radiation that reaches the ground through the steepness and orientation of the slope. In mountainous regions, elevational differences can directly affect the climatic inputs of precipitation, but most landform modifications of water supplies deal with how water moves after it has reached the ground. The depth and porosity of the soils govern whether water is drained freely or is retained for some time in the rooting zone. The topographic position on the landscape (e.g., hilltop, lower slope, or floodplain) further affects the water status of a site. And lastly, the specific nature of the soil texture (sand, silt, clay content) adds a further modifying force by affecting water retention and the capacity for nutrient exchange. However, most of the important attributes of a site can be described by **climate** and **landform**.

Sites can be usefully categorized in terms of the limitations imposed on plant growth by shortages of one or more of the basic factors (light, temperature, water, nutrients). The supply of water is generally the most important factor that differentiates sites. The physiological availability of water is limited by absolute shortages (e.g., freezing from low temperature), or the inability of roots to take up water that does not have enough oxygen to allow root respiration, such as in bogs and swamps. Carbon dioxide is deficient in some circumstances, though with ever increasing levels in the atmosphere there are signs that this is acting as a fertilizer, but in other instances another nutrient becomes more limiting (Ainsworth and Long, 2005; Finzi *et al.*, 2006; Finzi *et al.*, 2007). Solar energy mostly varies on a regional scale, but slope and aspect in steep landscapes can alter temperature regimes and consequently the water status of a site, even if precipitation is not affected. The effect of soil nutrients is exceedingly variable; in general, they affect growth rates more than species composition and tend to be less important than water, though there are plenty of exceptions to this, particularly on nutrient-deficient sandy or highly weathered clayey soils (Schoenholz, Van Miegroet, and Burger, 2000).

The interaction of these physical and chemical factors clearly determines what kinds of organisms can survive on a site and also how well they can grow there. However, the organisms themselves become additional factors to consider within the local environment. Consideration must be given to how they interact with each other and how they may affect the particular species that the forester may be trying to grow either in a facilitatory (e.g., nitrogen fixation) or negative way (e.g., browsing). In this sense, browsing animals, mycorrhizal fungi,

insects, or other plant species, to name only some, become part of the site or habitat factors. Regardless of the semantics, these biological factors are also part of the environment that must be carefully considered in any silvicultural decisions. In summary, the choices of tree species should be dictated by pests and other damaging agencies, as well as by physical conditions of the site mentioned earlier.

The Use of Site Analysis in Silviculture

Because it plays such a fundamental role in controlling the factors important to forest growth, regional climate should be the first consideration in site classification. Koeppen's classification of climate (Kottek *et al.*, 2006) is especially helpful because it is an attempt to categorize physical climatic data by using the vegetation as the most sensitive measuring device. However, if the silviculture relies entirely on species and genotypes already existing in the region, there is little real necessity of assessing the climate because it can be presumed that the plants are well adapted to it (though this may now be negated to some extent with climate change). However, it is always critical to know about the climate when choosing to make the decisions of introducing a new species or genetic variety through planting or seeding.

Site quality assessment should be incorporated into silviculture in the following way. The first step is to measure site quality at one or more points by making observations or measurements. These usually involve tree heights and ages, presence or absence of certain indicator plants, or measures of soils, as will be described later in this chapter. The goal of such an assessment is either to determine quantitatively the productive potential of the land in order to predict yields, or to identify the ecological sensitivity and uniqueness of the land for conservation and land use planning. In industrial forestry, so much emphasis is placed on yield prediction that the utility of site classifications for guiding decisions about silvicultural treatment and species composition is often overlooked. These classifications provide diagnostic clues about those factors of the particular site that will control such variables as the susceptibility and vulnerability of trees to damaging agencies, the nature of problems with competing vegetation, and responses to various silvicultural treatments. It is only after defining site quality using a site classification system that smaller management units within this can then be defined as **stands**, the base vegetation unit for silvicultural treatment. Stands are further distinguished based on differences in land use or disturbance history (i.e., vegetation age class), species composition, and stocking (i.e., spatial arrangement and density of vegetation) (Fig. 3.1).

A problem common to many site classification methods is that they do not provide a clear way of expanding the assessment of site conditions from a point or plot to a spatial scale (Carmean, 1975; Rowe, 1996). Also, the size of the landscape unit that has a uniform site quality is not necessarily the same as an area with a uniform vegetation type or **cover type**. Cover types are the result not only of site conditions but also derive from a variety of human and natural disturbances. Foresters generally must rely on their knowledge of correlations between soils, landforms, and vegetation in a region to make an estimate of the spatial extent of uniform site conditions. Frequently, no systematic technique is available to guide this step of the process. This means that to achieve a proper stand and site classification map the first step is to construct preliminary cover-type maps. Within this map, stand units can be delineated, based on age, composition, and stocking. It is only after more resources are provided and more field experience has been gained that a site classification is developed that then allows the forester to better redefine stands within the inherent productive capacity of the landscape.

There should be two kinds of maps available for foresters to use in managing forest land. One depicts current vegetation in the form of a **stand map**; the other is a **landform map**, classifying units that define site and that predict suitability for different ecological communities, species, and growth rates. The development of the second type of map requires a good deal of time and effort, but, once available, it reduces or eliminates the need for point assessments of site when considering treatment alternatives for a stand. For these reasons, there is increasing interest in developing site assessment techniques that lend themselves to mapping. Such examples have been well developed particularly in the upper midwest (Host *et al.*, 1996) and the west (Pojar, Klinka, and Meidenger, 1987).

Various methods of site assessment used in silvicultural practice are described in the next sections of this chapter. More complete reviews of these techniques can be found in Hagglund (1981), Tesch (1981), Vanclay (1992), Kimmins (1997), and Barnes *et al.* (1998).

Use of Tree Growth as an Indicator of Site Quality

The most common methods of assessing site quality depend on using direct measurements of vegetation productivity as the basis of classification. Prediction of the timber yield of a given single species on a site is frequently the specific interest, and the best criterion of this is a recorded history of production on the specific tract itself. However, this is available only where detailed records of careful management have been kept for many decades. In the absence of such records, it has become common to use rates of growth in height of the largest trees of a given species as substitute indicators of stand productivity.

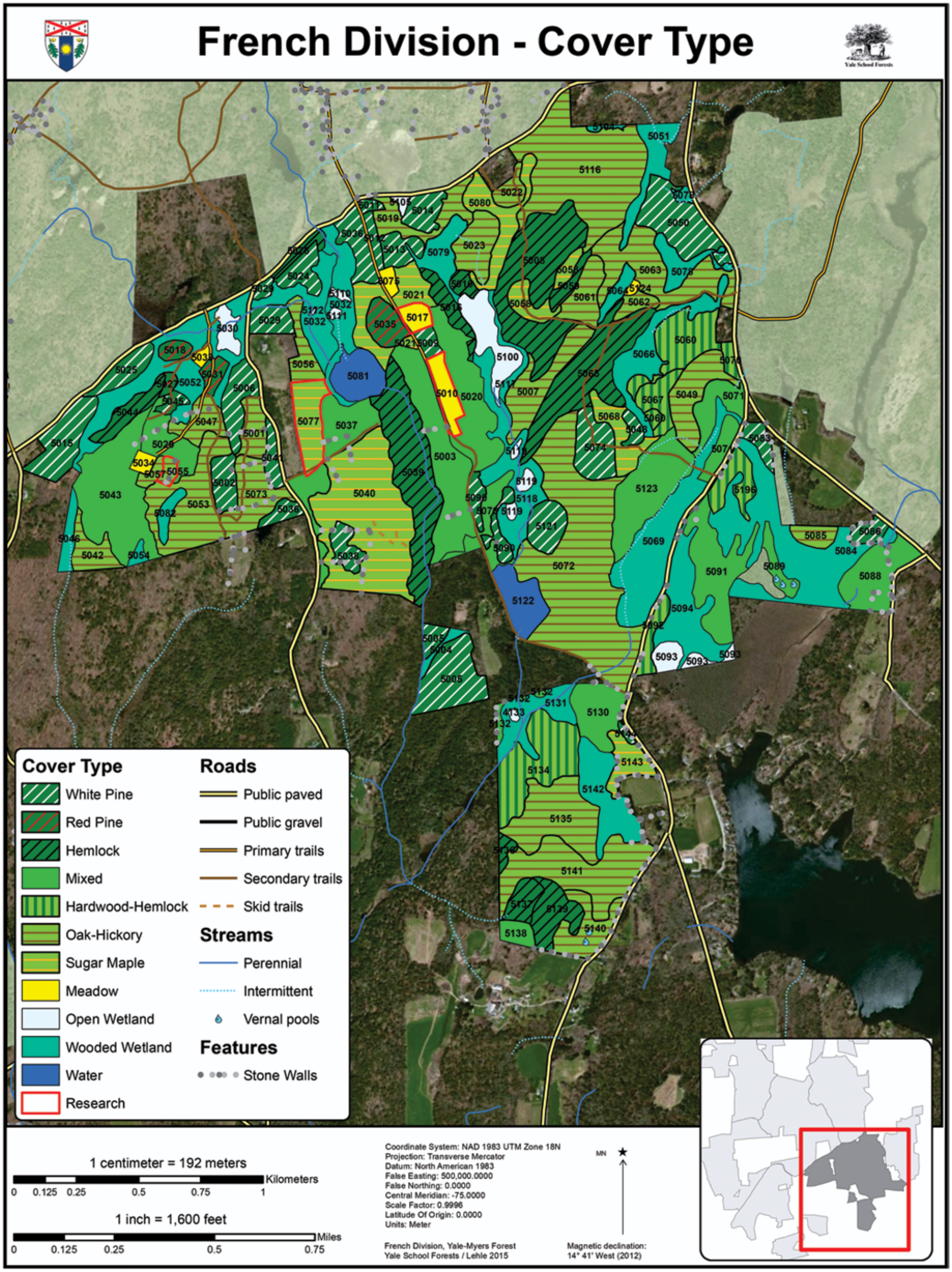


Figure 3.1 Depiction of a cover type and stand map for a division of The Yale–Myers Research and Demonstration Forest in northeastern Connecticut. The stands are identified by numbers. The cover types are depicted by color codes in the key. *Source:* Yale School of Forestry and Environmental Studies.

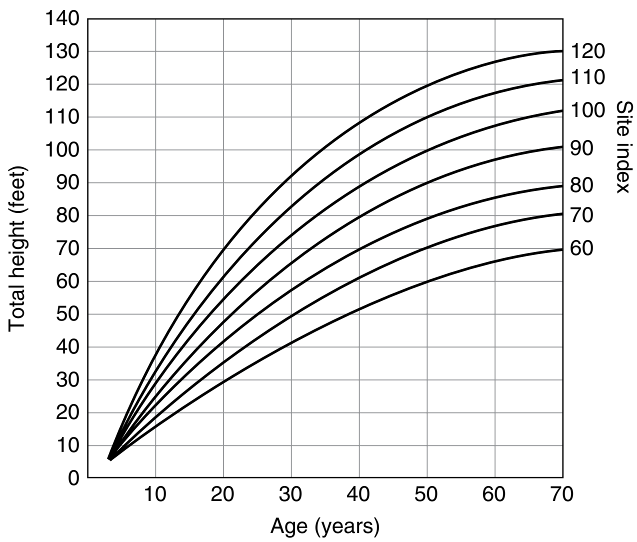


Figure 3.2 Site index curves for loblolly pine based on stem analyses of trees growing in the coastal plains of Virginia, North Carolina, and South Carolina. These curves use base age 50 at breast height as the basis for measurement and indicate seven site classes ranging from 60 to 120 feet. *Source:* Hamilton, 2000.

The most common method in use is **site index**, the average height of the dominant and codominant trees of an even-aged aggregation of trees at some index age. The index age is 50 years unless otherwise stated; the logical index age is ordinarily somewhat less than that of a normal rotation for the tree species in question (e.g., 50 years is commonly used for oak with rotation ages of 100). Other common index ages are 20, 25, and 30 years for some of the faster-growing pines and eucalyptus species. Curves of average height over age for dominant and codominant trees have been developed using stem-analysis techniques for many species in several regions (Fig. 3.2). In practice, site index is measured by determining the height and age of a sample of trees of a single species on a site. The appropriate standard curves are then used to extrapolate from the measured heights and ages to determine height at the index age. This height is referred to as the site index. The inference that can be drawn from an index is that the tree species growing on a particular site will follow the height growth pattern of the standard curve for that site. The number of trees measured and the method of choosing those trees can affect estimates of site index (Zeide and Zakrzewski, 1993). The criterion of crown class is frequently used, with the average height of a sample of dominant or codominant trees being the most common selection protocol, but the average height of dominant trees alone can also be used. The number of trees selected for measurement varies widely. More precise selection methods have also been developed, and two that are frequently used are: (1) **predominant height**, defined as the average height of the tallest 40 trees/acre (100 trees/ha); and (2) **top height**, defined as the average height of the 40 trees/acre with the largest breast-height diameters (Spurr, 1952; Clutter *et al*., 1983; Avery and Burkhart, 2002). Other systems use a fixed percentage of trees of a certain class rather than a fixed number. Although sampling techniques vary and are identified by different names, they do not differ from site index in concept. What is important is understanding how the site index is constructed and what specific sampling regime and measurements are recommended.

The site index approach is based on the observation that the rate of height growth of the leading trees is well correlated with the productive potential of a site but is not altered significantly by ordinary variations in stand density (although very high or low density may influence the height growth of species). In the simplest application, it is necessary that the index trees have always been the leading dominant trees and have not been suppressed at any time. Periods of very slow diameter growth observed in increment cores taken to determine age are used as an indication that a tree was overtopped for part of its life. Such trees are generally eliminated from use as sample trees for site index measurement. Many dominant trees grow slowly in height during an early establishment period. This occurs when seedlings compete with dense weeds or start as advance regeneration. One way of avoiding this problem is to assess each tree's age at breast height and to take that point as the zero height level. This approach has been incorporated in some standard site index curves (Fig. 3.2).

Use of site index has become widespread, partly because it is incorporated into the yield tables developed for many commercial timber species. In fact, site index is sometimes expressed in terms of the mean annual increment of stands where growing space is fully occupied instead of height, but this is simply a matter of using the value from the associated yield table. The basis for determining site class of a stand is still the measurement of the height and age of a sample of its largest trees.

Determining tree age from increment cores is the most time-consuming part of measurement and often limits the data collection to only a few trees. Site index is easiest to use in plantations or other stands with a narrow range in ages, where only heights need to be measured for most trees. These are the situations in which a sample size of as few as 5 trees/acre (15 trees/ha) is sometimes used. In many other cases, where stands are more variable in age class, as many as 40 trees/acre (100 trees/ha) are measured.

In cases where measurement of a large sample of trees can be used in conjunction with height curves developed for that region, a precise estimate of site index can be

determined. However, in most situations, there are enough sources of error in data collection, extrapolation using height growth curves, and other aspects of "measuring" a site that it is good to refrain from the spurious precision implied by expressing site index to the nearest foot or meter. One common antidote to this is the practice of assigning sites to not more than five or six rather broad categories of site quality classes, commonly denoted by Roman numerals. This is often a sufficient level of precision for making decisions about silvicultural treatments.

The different uses of site index can be seen in the example of management of eastern white pine in the northeast. White pine can grow on a wide range of sites, with productivity increasing on landforms and soils with greater moisture-holding capacity. Site index curves and associated yield tables can be used to predict the productivity of pure pine stands. However, because of the difficulty of controlling early hardwood competition on moist sites, pine is generally grown in pure stands only on relatively dry soils. The site index of oak is frequently used as a standard to classify sites based on the competitive ability of hardwoods. Sites have been divided into three categories with recommendations for (1) converting to pure pine; (2) favoring mixed pine and hardwood; or (3) favoring pure hardwood stands being associated with increasing values of oak site index (Lancaster and Leak, 1978).

Some methods of expanding or simplifying the use of site index have been developed. If the tree species of interest is not present on the site, procedures can be developed to predict the site index of one species from that of another (Doolittle, 1958; Foster, 1959). The height-intercept method can also be used, in which the index variable is the number of years required to grow from one stated height level to another. This method works with trees that produce one internode annually, so that height growth can easily be determined for levels close to the ground. Current site indices are being constructed from longer-term plots and more permanent growth records than those that were originally constructed. Now more sophisticated dynamic site equations are being used that more closely model height growth relationships over time and change in site (Cieszewski, 2001; Diéguez-Aranda, Burkhart, and Amateis, 2006).

Site index is most useful for conifers because they have a well-defined height that is relatively easily measured. Many hardwood species have rounded, spreading crowns that are more difficult to measure. The range of heights obtained in even-aged hardwood stands, even with careful measurement, is sometimes so wide as to make site index calculations almost useless. Most site indices have been constructed for species that can tolerate a wide range of sites, thus the usefulness of an index. Such techniques are not useful for tree species that are site restricted and thus their presence or absence can be used as more an indication of a particular kind of site. And finally, site indices have generally been constructed primarily for tree species that are of commercial value and so gauging their productivity on a range of planting or regeneration sites is important. In North America, such species include but are not limited to: loblolly pine (Amateis and Burkhart, 1985), lodgepole pine (Cieszewski and Bella, 1989), ponderosa pine (Milner, 1992), slash pine (Borders, Bailey and Ware, 1984), Douglas-fir (Monserud, 1985), trembling aspen (Chen, Krestov, and Klinka, 2002), white pine (Beck, 1971; Parresol and Vissage, 1998), white spruce (Alemdag, 1991) and the upland oaks (Carmean, 1972).

Other methods have been devised to replace site index in order to overcome its limitations in assessing site conditions. These include methods that: (1) lend themselves to dividing a landscape into easily mappable management units; (2) work when no trees are present on a site; (3) work in tropical regions where trees do not necessarily form annual or even seasonal rings; or (4) are based on field observations that do not require measurement of tree heights and ages. Many of these methods involve prediction of site index from other parameters.

Understory Plant Indicators and Habitat Types

Species composition can also be used to assess potential productivity, limitations set by environmental factors, and species suitability. The best-known methods, originally developed in Finland by Cajander (1926), involve use of the herbaceous plants that grow beneath stands. The underlying principle is that some of the small plants are much more sensitive to variations in site factors than large trees are (Daubenmire, 1976). Some of these plants have high indicator significance, whereas others, those with broad environmental tolerances, have little. More recently, the quantitative testing of niche theory and the applied use of understory species as site indicators have substantiated the work of the older more qualitative literature (Gilbert and Lechowicz, 2004). However, this work has also clarified the more complex interactions that can occur irrespective of site in regards to anthropogenic and natural disturbances. Such disturbances also influence understory species' presence and abundance, and therefore can be a misleading indicator of site productivity (e.g., fire history; colonization by invasives; herbivory impacts from deer) (Honnay, Hermy, and Coppin, 1999; Knoepp *et al.*, 2000; Rooney *et al.*, 2004). Use of plant indicators for site classification is therefore most successful where climatic conditions are restrictive, as in the boreal forests

where these methods were originally developed. In those and other forests where large areas are dominated by a single overstory generalist species, distinguishing among several understory species can be used to predict site index without measuring tree heights or ages. There are, for example, large areas covered with Douglas-fir (Green, Marshall, and Klinka, 1989), but much information can be obtained about the site by noting whether the understory has sword ferns (an indicator of richer, higher-fertility site) or rhododendrons (an indicator of a poorer, lower-fertility site). In most cases, understory plant indicators are no longer used alone but are incorporated into more holistic approaches such as in the white spruce and lodgepole pine regions of Canada (Strong *et al.*, 1991; Meilleur, Bouchard, and Bergeron, 1992).

Especially in western North America (Daubenmire and Daubenmire, 1968; Steele *et al.*, 1981), some success has been achieved with using the late-successional plant communities as the basis for site classification. In this approach, a set of site units, referred to as **habitat types**, is identified by the characteristic overstory and understory species that occupy certain elevation and physiographic conditions; the names of the habitat types are taken from dominant species in each layer (e.g., *Pseudotsuga menziesii/Symphoricarpus albus* habitat type). A taxonomic key based on the presence of indicator species was developed and is used as the basis for field identification. Field techniques involve the use of **releves** – a method of plot measurement that quickly assesses the relative abundance of species in each vegetation layer without detailed measurement. Precise measures of species' abundances are not necessary because the presence or absence of certain indicator species is often the criterion most indicative of site conditions.

Habitat-type mapping has been used throughout the Rocky Mountain region as the basis for predicting site quality, assessing wildlife and livestock forage productivity, estimating water production, and other purposes. This mode of site analysis and mapping works best where species composition is mostly the result of natural processes (e.g., Fig. 3.3). Even in those cases, it is necessary to use elevation and other landform features to guide mapping where late-successional vegetation is not present. This is most easily done where strong variation in elevation and topography exists.

The habitat-type approach has been used on a more limited basis in areas that have been heavily disturbed by agriculture, such as the Great Lakes region (Kotar, Kovach, and Locey, 1988), southern and central New England (Whitney and Foster, 1988) and the White Mountains of New Hampshire (Leak, 1980, 1982). Important differences in site types have been determined by studying correlations between physical site characteristics and the composition of relatively undisturbed vegetation in the limited areas where such vegetation

(a)

Figure 3.3 **(a–e)** A series of photographs showing old-growth forest vegetation characteristic of markedly different sites, each requiring correspondingly different silvicultural treatment, all in northern Idaho. **(a)** The lowest and driest site with a pure stand of ponderosa pine.

(b)

(c)

Figure 3.3 (Continued) **(b)** An open stand of ponderosa pine on a south-facing, dry slope at middle elevations. A closed stand of the so-called western white pine type, such as shown in c, occupies the opposite north-facing slope. **(c)** A mixed stand of the western white pine type on a mesic north-facing slope. The nearest tree is a western larch; the one to its left is a western white pine; the one with vertically striped bark to the left of that is a western redcedar; some of the understory saplings are white firs.

(Continued)

(d)

(e)

Figure 3.3 (Continued) **(d)** A 225-year-old stratified mixture of the western white pine type on a mesic valley-bottom site below the stand shown in b. Among the other species present are western larch, western redcedar, and western hemlock, with the two latter species in the lower strata. **(e)** A pure stand of white-bark pine characteristic of very cold sites at high elevations in the same locality as a and d. *Source:* **(a–e)** US Forest Service.

could be found. In these regions, landforms and soils have been used as the basis for mapping because of the scarcity of undisturbed vegetation over most of the landscape. The importance of landform in identifying habitat types in the field is evident in the White Mountains classification system. Here the type of glacial deposit is the fundamental basis for mapping land into one of 11 habitat types and is also used as the name for each type, instead of using the names of indicator species (Leak, 1982). There is therefore a rich history of using plant indicators of site but its usefulness varies by region and land-use history.

Analysis of Soils and Topography

Considerable interest has long existed in developing ways to predict potential forest productivity directly from soil and topographic variables, without using trees or other vegetation as indicators. Many studies have developed predictive mechanisms in the form of multiple regression equations in which site index is determined from a number of independent site variables (Armson, 1977; Pritchett, 1979). This approach to site classification often requires deep digging to examine the soil structure and collect samples for subsequent determination of physical and chemical properties (Soil Survey Staff, 1975). Because it has generally proven impractical, there are few examples of such systems being put into practice. These techniques have been most useful where large plantation projects have been established in areas in which forest vegetation was sparse or absent. No alternative methods were available in these situations, and financial resources were available for detailed soils analysis and mapping. One example of this is the Baker–Broadfoot (1979) method used to evaluate sites for hardwoods of the lower Mississippi region of the southern USA. The method uses simple site/soil characteristics for selecting species for reforestation. It has proven useful despite the flat landscape, just small topographic differences can cause dramatic changes in hydrology and soil texture.

The greatest value of soil-site studies has generally been for basic research that has elucidated the most important factors controlling forest growth, even if some of these are not easily measured. The variables that define the availability of water have been identified as the most critical. These include depth to bedrock or hardpans, which determines the depth of the rooting stratum, and soil texture, which governs the capacity of that stratum to store water (Barnes *et al*., 1998). Variables that measure nutrient status have generally been less important. To be useful in silvicultural practice, this technique depends on assessing factors that can be measured on one visit to the site. Therefore, the annual regime of soil moisture must somehow be deduced from appropriately selected, semipermanent, observable parameters of soil and site.

The shape of the terrain is often key, usually because it tells so much about the water relations that are usually the chief ruling factor for plant growth. For example, the lower slopes of most hillsides are concave; thus, they receive more water from upslope than directly from the sky. Water from the convex hilltop seeps downslope, leaving the upper slopes robbed of soil moisture. The boundary between convexity and concavity sometimes defines differences in species composition and productivity. Unless they have sandy soils, very flat areas can be poor sites full of stagnant, oxygen-deficient water. If the terrain is steep, the slopes that face the sun can be very dry while the opposite shaded ones are comparatively moist. This difference can be enough to induce grassy brushfields on sunny slopes and closed forest on shaded ones in climates with long dry seasons, such as in the Rocky Mountains. Good examples of the use of terrain as an index to site productivity have been developed for the Appalachians (McNab, 1989, 1993). Current use of digital elevation maps and geographic information systems (GIS) can be very useful for developing a terrain index (Bolstad, Swank, and Vose, 1998). High-resolution spatial imagery can now depict topographic relief at refined scales that allow modeled water, solar radiation, and temperature gradients to predict and create vegetation and productivity maps (Dymond and Johnson, 2002; Thenkabail *et al*., 2003; Wulder *et al*., 2004).

An analytical and predictive understanding of site variables can often be based on good knowledge of geology and especially geomorphology. The climatic factors that have weathered rocks and moved the products of natural erosion also determine the composition and shape of the parent materials from which soils are formed. If it is known how the parent materials got where they are, it becomes possible to learn a good deal about the extent of a particular kind of terrain form and its ability to support forest growth merely by viewing it from a distance or on a topographic map. Knowledge of surficial geology helps not only in determining species composition and predicting yield, but also in developing wildlife habitat areas, building roads, planning logging, protecting watersheds, and controlling erosion.

The shortcomings of direct soil analysis techniques described above can be overcome by using soil type maps. These are available for many parts of the world and contain information on the variables that are difficult to determine in field sampling. However, these maps have proven to be of surprisingly little value for silvicultural use because nearly all soil classifications have been devised with agricultural needs in mind and therefore only focus on the characteristics of soil in the top 3 ft (1 m). Forests are much deeper rooting and require additional characteristics for interpretation of their growth. Although people who map the soil must have a detailed understanding of the relationship between topography and soils, landform characteristics are generally not an integral part of the soil-typing process. However, landform and its association with soil depth are signature characteristics that can be used to interpret growth and composition of forests (Rowe, 1984). A case in point is that the old Soil Conservation Service maps (now digital) still used throughout the US are a useful first effort, but they often need considerable verification and realignment when on the ground.

Each kind of landscape – mountain ranges with volcanic deposits, ancient peneplains with heavily weathered soils, rolling terrain with glacial deposits, and many

others – has a distinctive set of landforms. Knowledge of these is often more important to foresters than are the details of soil structure. Maps of soils that use landform as an integral part of the definition of mapping units are very valuable for silvicultural planning (Rowe, 1984). One example of the effects which different kinds of landforms and soils have in controlling the composition and vigor of forest vegetation is found on the flood-plains of snakelike meandering rivers. Frequent flooding events continually destroy and rebuild the "bottomlands" through which they flow (see Box 3.1).

Ecological Site Classification

Most of the site classification methods described in this chapter are not used alone, but are combined with others to make them more useful and more efficient in application. Some multifactor systems explicitly recognize that a combination of the four basic parameters (climate, landform, soil, and vegetation) provide the most complete approach. In many regions, maps already exist for all or most of these factors, and some efforts at multifactor classification are based on using these multiple layers of information to define a set of distinctive site units. However, unless these are based on recognition of the relationships between these four elements, such systems cannot be considered "ecological" (Barnes *et al.*, 1998), and may be difficult to implement.

Ecological site classification is based on a hierarchy, with climate as the dominant factor at the regional scale, and landform and soil at the landscape unit scale (Bailey, 1995). These factors generally vary along gradual gradients rather than across sharp boundaries. The importance of vegetation in the development of such systems comes in defining distinctive climates, landforms, and soil characteristics that are correlated to important differences in vegetation composition and productivity. Thus, an ecological approach would seek to define a classification of these distinctive units before mapping can commence.

This approach is the basis for defining different climate types, as in British Columbia (Pojar, Klinka, and Meidinger, 1987), where large geographic units with similar climates and forest types have been defined and mapped (Fig. 3.4). These "biogeoclimatic" units are useful for such things as identifying fire-climate zones for protection purposes or defining zones for the movement of seeds, but their most fundamental use is for defining the boundaries within which a smaller-scale site-classification system can be applied.

Site units ranging in size from 10–100 acres (approximately 4–40 ha) are of greatest value in silviculture, and are defined by landform and soil within a climatic zone. These fundamental units are considered "natural" or "ecological" units because they are not based on a derived feature (such as the height growth rate of a particular tree species).

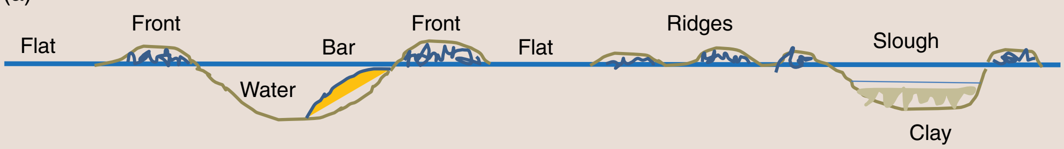
Box 3.1 A cross-section, in exaggerated vertical dimension, of the different landforms that develop on the flood-plains of meandering rivers, shown at a time when the water level is normal (i.e., not at flood stage).

Fig. 1 shows most of the kinds of terrain; differences in elevation of as small as 3 ft (0.9 m) can cause major changes in forest composition. Hodges (1995) described these remarkable differences in the bottomland hardwood forests of the southeastern US. The highest terrain, best soils, and richest species composition are found in the "fronts" right on the banks of the rivers where fine sand is deposited when floodwaters are decelerated as they spill over the banks of the river. "Ridges" are former fronts that have been left when the course of the river shifts sideways or a loop is suddenly cut off. Their luxuriant forest vegetation, which may include such species as cherrybark oak, yellow-poplar, and sycamore, differs little from that of the fronts. The series of ridges shown is a place where the river course gradually shifted from left to right before it was cut off. The "slough" that formed in the cut off loop is a place where water stands most of each year and very tight clay formations are deposited. The species that grow slowly there are those such as bald-cypress, tupelo gum, and water hickory that can survive in standing water. "Bars" composed of coarse sand form along the main river where the current is decelerated slightly as it flows around bends. Fast-growing, intolerant, light-seeded species, such as willows and cottonwood poplars, start on the bare soils exposed there. The "flats" are level soils full of clays that are deposited there when water stands for many weeks after typical floods. These wet, poorly aerated soils support such species as red maple, green ash, sweetgum, Nuttall oak, and sugarberry, that can withstand physiological dryness. Similarly distinctive guilds of species grow on these kinds of landforms along meandering rivers throughout the world.

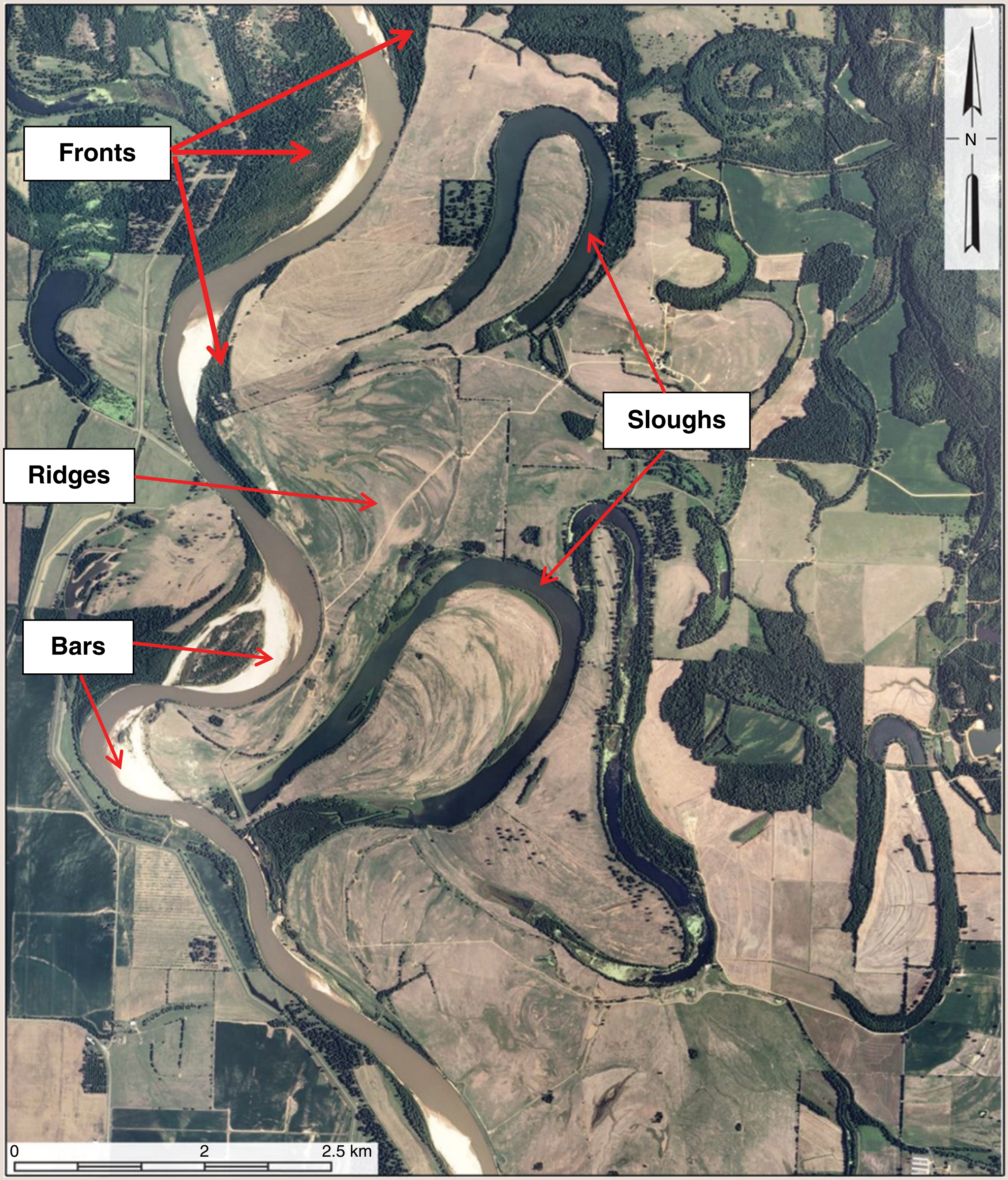
The Baker–Broadfoot method of site evaluation (Baker and Broadfoot, 1979) for southern bottomland hardwoods is a reflection of the landform processes described above, that determine changes in species composition. The site classification guide suggests species suitability for plantation establishment and is determined by using tables that describe the ranges of soil physical properties, moisture availability during the growing season, nutrient availability, and soil aeration. The guide is commonly used across the Gulf States for bottomlands.

Box 3.1 (Continued)

(a)



(b)



Box 3.1 Figure 1 **(a)** Topographic relief of a bottomland in the lower Mississippi.*Source:* Mark S. Ashton. **(b)** An aerial depiction of topographic relief of the Red River, Arkansas, a tributary of the Mississippi River. *Source:* Wikimedia Commons, The Free Media Repository.

(a)

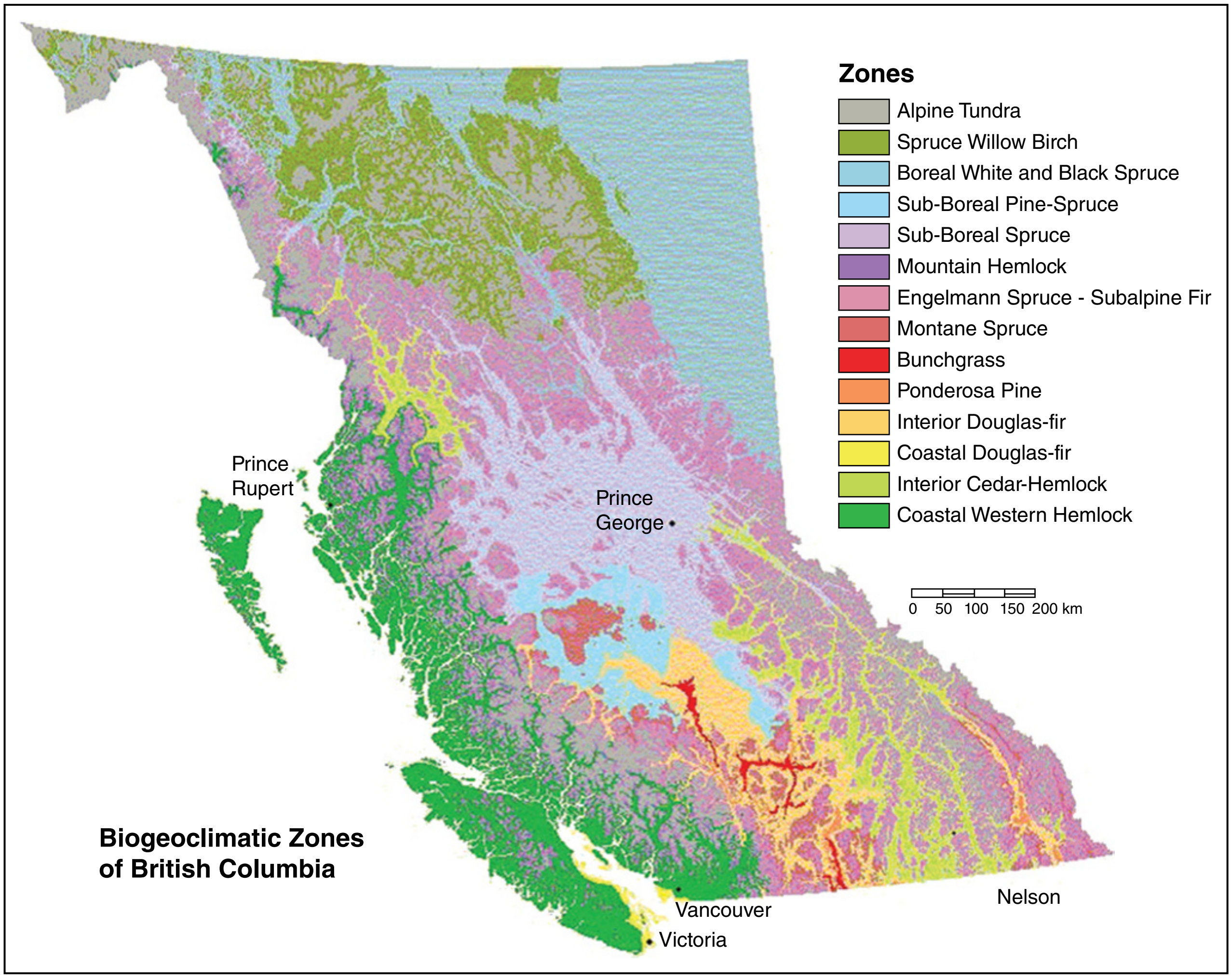


Figure 3.4 **(a–c)** Ecological site classification for British Columbia with an example of the mountain hemlock type. **(a)** An illustration of the biogeographic climate forest zones of British Columbia.

Rather, they are defined by the combination of climate, landform, and soil that controls the energy and material inputs to the ecosystem and are correlated with characteristic vegetation. Mapping these units can be done using a combination of topographic and surficial geology maps, examination of soils, and identification of indicator plants. Because each unit defines a consistent set of environmental conditions, it can be used to predict many parameters, including stand productivity.

One such example of an ecological site classification system was developed for a glaciated, rolling landscape in the Great Lakes region where northern hardwoods, red pine, and white pine are the principal species (Barnes *et al*., 1998) (Box 3.2). A principal use of the system has been to identify those sites that are suitable for conversion to red pine and those that are best managed for mixed hardwood stands dominated by sugar maple. Because the site units are fundamental divisions of the landscape, they should maintain their usefulness as new management questions arise. Choice of species and other silvicultural decisions should be guided by an analysis of site or habitat, regardless of the method of classification or how the categories are named.

Stands as Management Units

The **stand** is the base management unit for applying any silvicultural treatment. **A stand is the smallest unit in forest mapping and can be defined as a spatial area where a group of trees is more or less homogeneous in regard to species composition, density, and age-class distribution**. Stands as spatial management units are usually delineated at smaller spatial scales as compared to a site-classification system. This is because within a site class, both natural and anthropogenic disturbances can vary, creating different successional compositions, age classes, and stocking densities,

(b)

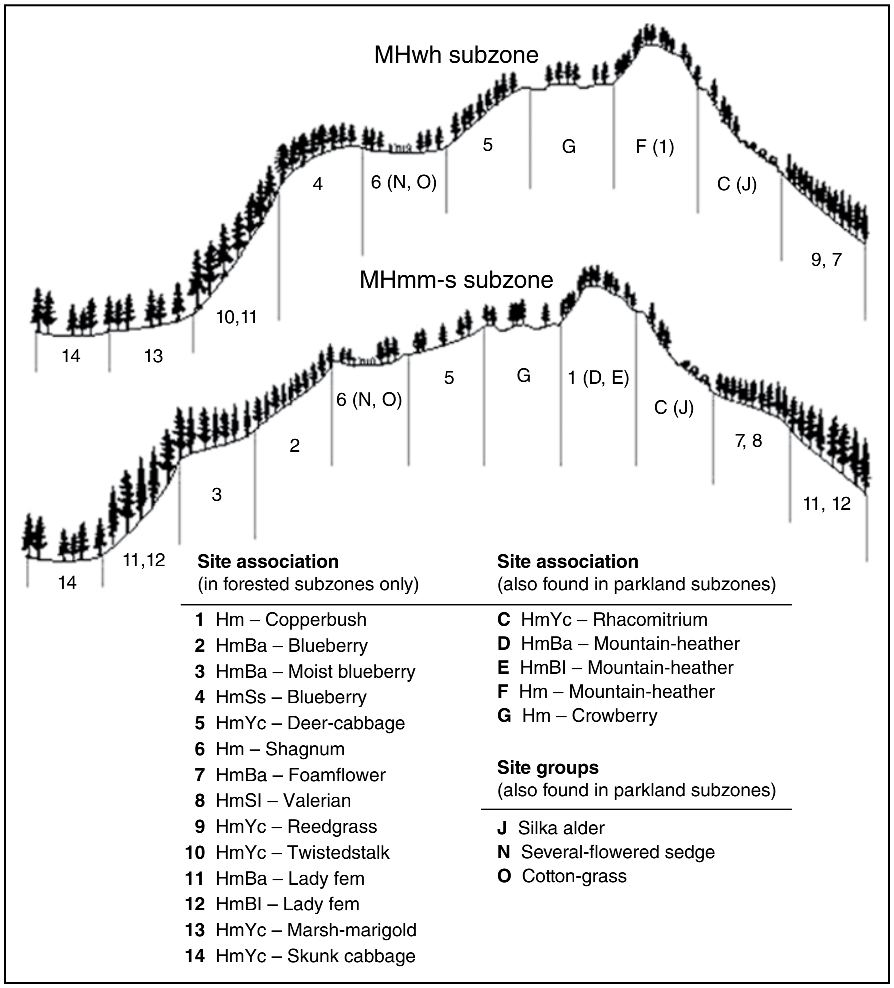


Figure 3.4 (Continued) **(b)** A cross-section of the Mountain Hemlock Zone physiography as an example of defining site differences within a forest climate zone. The Mountain Hemlock Zone is restricted to the subalpine elevations of coastal mountains of southwest British Columbia.

(Continued)

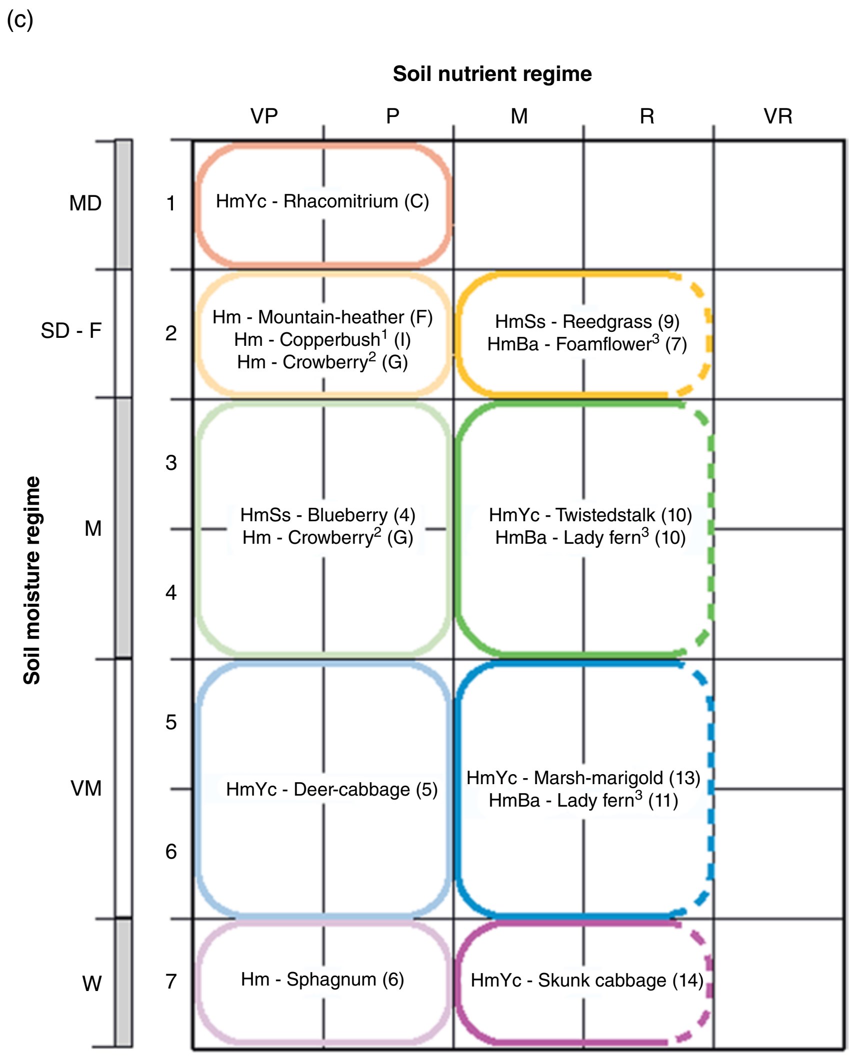
all of which create differences in forest structural heterogeneity and growth and therefore stand management units. It is unusual to define a stand at spatial scales larger than a site class. This is because stands that cross a site classification by implication would mean differences in site productivity, growth rates, and species composition making any one silvicultural treatment across such an area very difficult to implement. However, it does occur for extensive kinds of low-intensity management and for social values that are not intimately and directly dependent on forest structure and composition, such as in watershed management.

Stands as Defined by Age Class

Defining differences in age class is one very important method of delineating a stand. Regenerative disturbances, whether naturally or artificially induced, determine when new trees appear or start active development on any given unit of ground area. Each aggregation of trees that starts as a result of a single disturbance is defined as a single **cohort**. If the range of ages of trees within the cohort is very narrow, the new aggregation is regarded as a single **age class** which is also **even aged**.

For purposes of planning for cuttings and forecasting the future growth and yield of stands, it is necessary to ascribe ages to stands or components of stands that have arisen at different times in the past. This is no problem if the trees all germinated or were planted during the same year because they are clearly of the same even-aged class.

Quandaries develop when the effects or characteristics of the disturbances and the sources of the regenerating trees are so variable that the true ages vary widely. Confusion can be reduced by recognizing the difference between **chronological age**, which is the true age of the plant, and **effective age**, which is the number of years since the trees were free to start rapid growth and development into a new forest. This would be very much the



[1]only in the mainland portion of the MHwh subzone on slightly dry sites
[2]only on fresh to moist sites at the upper elevation limit of the MHwh subzone on flat terrain
[3]only in the mainland portion of the MHwh subzone

Figure 3.4 (Continued) **(c)** The temperature–moisture association with herbaceous indicator species for the Mountain Hemlock Zone. Soil nutrient regime: VP – very poor, P – poor, M – medium, R – rich, VR – very rich; soil moisture regime: W – wet, VM – very moist, M – moist, SD-F – somewhat dry, MD – moderately dry. *Source:* **(a–c)** British Columbia Ministry of Forests, 1995a. Reproduced with permission from the Province of British Columbia.

case with release-type disturbances whereby seedlings of advance reproduction origin could be many years older and of varying chronological ages as compared to their effective age at time of release. For all intents and purposes, age from release has been the defining attribute for determining age class.

A cohort therefore has an effective age even if the chronological age varies widely. It may include trees that germinated or were planted in a single year, those that sprouted from stumps or roots that were really hundreds of years old, advance regeneration of many different heights that had accumulated over many decades, or new seedlings that slowly appear for several decades after a severe disturbance. In such cases, the effective age of the whole is best dated arbitrarily from the time of the regenerative disturbance. This does not mean that one may blithely adopt any assumption that the trees of the cohort are all the same because they were all put in the same pigeonhole.

In this book, the term cohort will not be used except in cases in which chronological and effective age might often differ. Terms such as age class, even aged, and uneven aged will be used not only where the range of chronological age within a class is very small but also where it simplifies discussion to refer to a cohort as an age class. The most notable examples of the latter exception involve long-established distinctions between "even-aged" and "uneven-aged" stands that are used in developing management for sustained yield (as in Chapters 11 and 13).

Box 3.2 The major features of an ecological site classification system for the McCormick Experimental Forest in the Upper Peninsula of Michigan.

Dryland Site Units

A portion of the classification of land units, defined by landform and basic soil characteristics, with indicator species listed; a total of 21 site units were used in mapping (Fig. 1).

Deep Soils – Bedrock Below 39 in (100 cm)

A) Level to gently sloping terrain (usually 0–5%)
   1) Excessively drained sand – **jack pine/*Vaccinium***
   2) Somewhat excessively drained sand and gravel – **sugar maple/*Maianthemum***
   3) Somewhat poorly drained sand – **maple/yellow birch/conifer/*Clintonia***

B) Moderately to steeply sloping terrain (usually >5 to <30%)
   1) Well-drained loamy sand – **sugar maple/*Gymnocarpium***
   2) Moderately well-drained sandy loam on northerly aspects – **sugar maple/*Viola***
   3) Excessively drained sand on steep southerly aspects – **white pine–hardwoods/*Maianthemum***

A More Complete Description of Two Site Units

This gives assessments of productivity and other parameters and suggests appropriate management objectives. Modified from Barnes *et al*. (1998).

Site Unit 2

Flat, outwash sand plain dominated by low-vigor and low-quality sugar maple. This site has the highest sand content and greatest susceptibility to drought of any sugar maple sites.

- Total height of old-growth sugar maple 69 ft (21 m) – low productivity
- No erosion hazard
- Suitable for mechanized equipment
- Low recreation and wildlife values
- Moderately high fire hazard
- Light competition from hardwoods

Recommendation: convert to red pine for greater productivity and fertilize to improve yield.

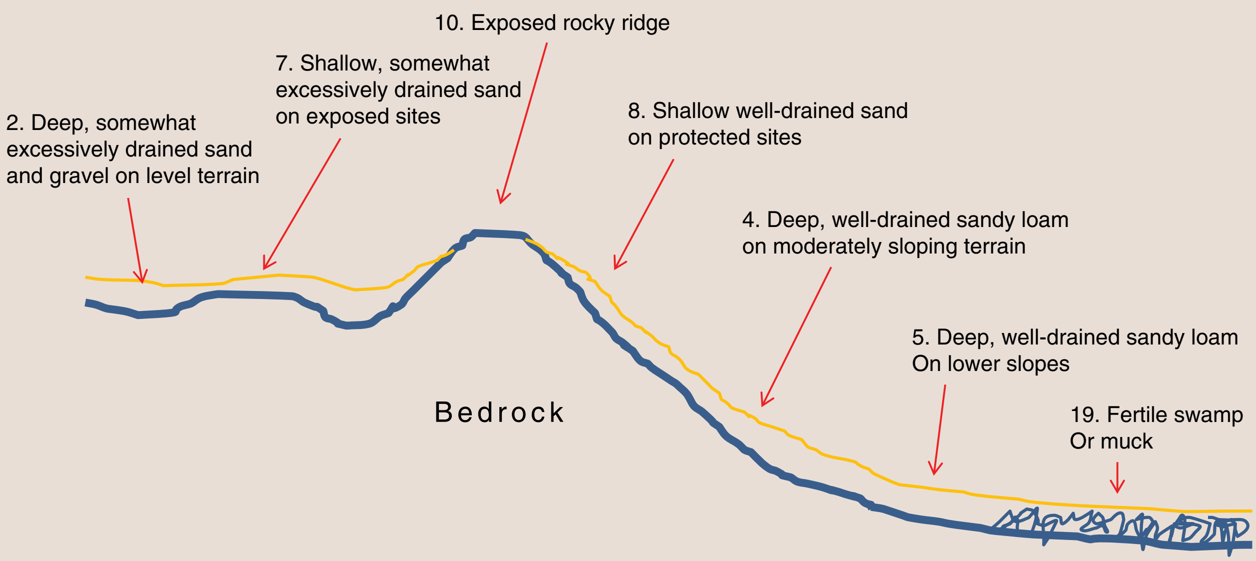
Site Unit 5

Lower slope with moist relatively fertile sandy loam soil. The site is dominated by high-quality, fast-growing sugar maple. The site has significantly less sand, more nitrogen, and higher pH than site units 1, 2, and 4.

- Total height of old-growth sugar maple 92 ft (28 m) – high productivity
- Moderate erosion hazard
- Suitable for mechanized equipment during July to November
- Moderate recreation value created by large trees and spring flora
- Low fire hazard
- Heavy hardwood competition

Recommendation: manage for high-quality hardwoods.

Source: Adapted from Barnes *et al*., 1998.



Box 3.2 Figure 1 A physiographic cross-section showing the relationship of some of the units to surficial geology and landforms. *Source:* Adapted from Barnes *et al*., 1998.

Differences in the timing of regenerative events create various spatial patterns of age classes or cohorts. The area occupied by a given cohort can be of any size, provided that it is large enough that some new trees can continue to grow in height without being arrested by expansion of the crowns of older adjacent trees. Only those truly regenerative events that leave new or small trees free to grow really affect the arrangement of age classes. Intermediate cuttings such as thinnings do not leave new trees free to grow, and thus have no effect on age-class arrangement.

There are three general types of age-class structure within stands: even-aged stands with a single age class, and uneven-aged stands. Uneven-aged stands can be further categorized as multi-aged stands with two to three age classes or all-aged stands with four or more age classes. In an **even-aged** (**single-aged**) or **single-cohort** stand (Box 3.3), all trees are the same age or at least of the same cohort. An **uneven-aged stand** that contains **two- to three-age classes** (**multi-aged** or **multiple-cohort**) represents an intermediate category in which the presence of at least **two** and sometimes **three cohorts** may be temporary or continuous. An uneven-aged stand that is **all-aged** comprises at least four age classes intermingled intimately on the same area. In reality all gradations of age distribution may be found in nature or created by cuttings designed to make way for new age classes or cohorts, but for management and communication purposes it is important to make these three basic age-class distinctions.

For some management purposes, a distinction is made between balanced and unbalanced uneven-aged stands. A **balanced uneven-aged stand** that is **all-aged** consists of four or more different age classes (or cohorts), each of which occupies an approximately equal area. The age classes are also spaced at uniform intervals all the way from newly established reproduction to trees near rotation age. Such stands, once created, may function as self-contained, sustained yield units. **Unbalanced uneven-aged stands** that are **all-aged** have four or more age classes that do not contain all the age classes necessary to ensure that trees will arrive at rotation age at short intervals indefinitely. Uneven-aged stands that are multi-aged (two- to three age

Box 3.3 Identification of age classes.

The profile of the top of a single-species stand is a good criterion of age distribution because trees of the same age grow in height at roughly the same rate, provided site conditions are uniform. An even-aged stand tends to be almost smooth on top. An uneven-aged stand is distinctly irregular in height, and the greater the number of age classes or cohorts, the more uneven the canopy.

There are several exceptional kinds of cases in which stands with more than one cohort can become rather smooth on top: (1) in very old stands, all of the trees, even those of very different age classes, may have culminated in height growth at a common level; (2) in some cases, isolated older trees that remain after cutting or some other disturbance may have decelerated in height growth sufficiently that more numerous younger trees around them catch up, and both age classes continue growing slowly in one smooth-topped stand; and (3) wind or some other climate phenomenon is continuously impeding upward canopy growth such that the canopy is flattened and windswept.

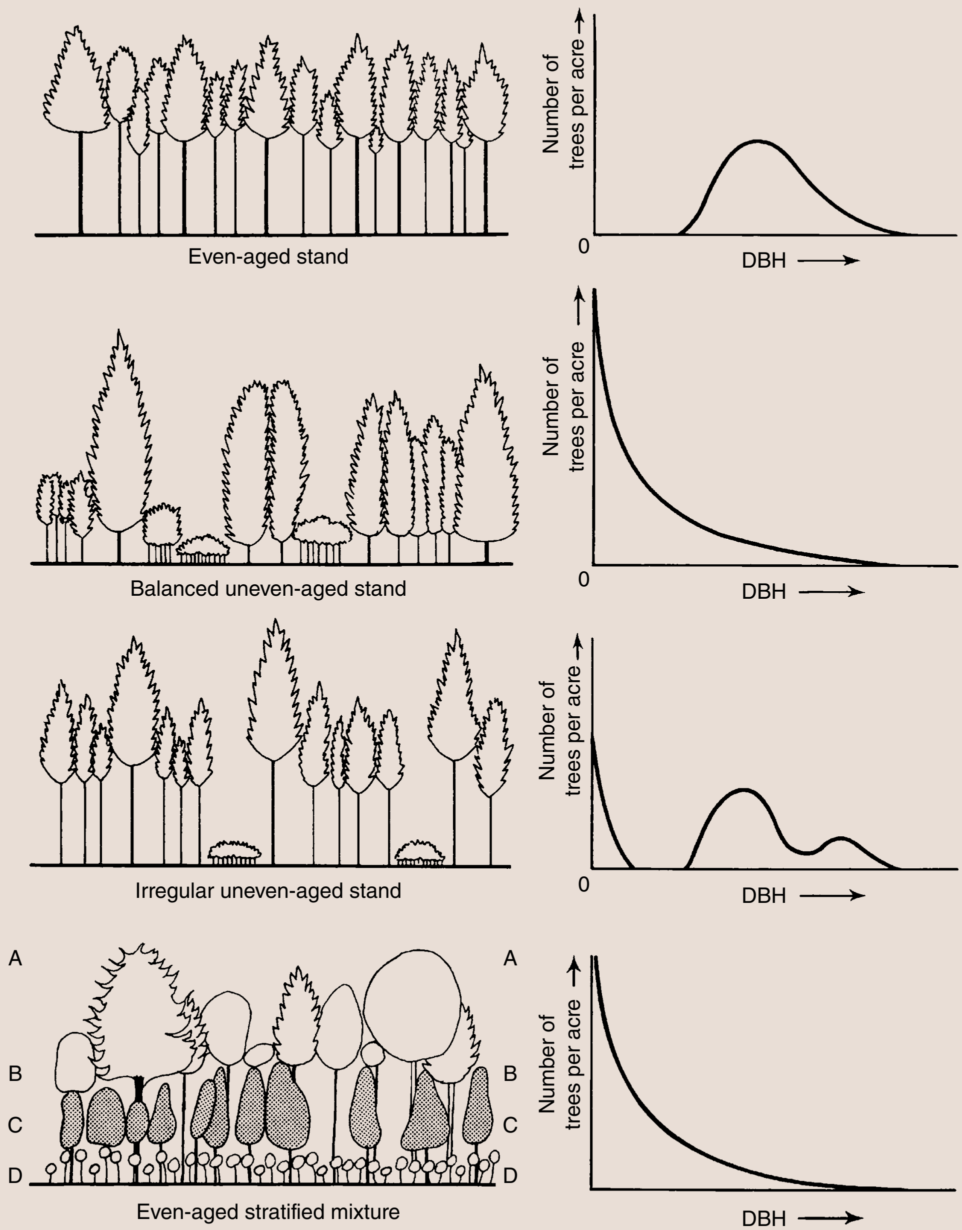
Although it might seem that fat trees are always older than thin ones, diameter is not a very good criterion of age and must be used as such with caution. The diameter growth of trees is much more variable than that in height. Therefore, the trees in an even-aged stand are not as uniform in diameter as they are in height. If a plot is made of the number of trees in each diameter class over diameter for a given pure even-aged stand, the distribution approximates the normal, bell-shaped curve (Fig. 1). The continuing loss of small trees from competition accounts for the typically abrupt slope of the left-hand side of the curve. It should be borne in mind that even-aged (single-aged or single-cohort) stands typically have a wide range of diameter classes; the age-class structure of a stand cannot be determined merely from the range of diameter classes present.

Uneven-aged stands that are balanced and all-aged are composed essentially of small even-aged groups of different ages. The distribution of diameters within each group also fits a bell-shaped curve, provided that the group consists of only one species or a number of species that grow at the same rate in height and diameter. However, as each little even-aged group grows older, competition reduces its number of trees, rapidly at first and more slowly later on; the point may even be reached where only one tree remains from 100 or more. Therefore, if each age class occupies the same area, the composite diameter distribution curve for a balanced uneven-aged (all-aged) stand (Fig. 1) follows an asymptotic relationship commonly referred to as "reverse-J-shaped," or simply "J-shaped."

If the age classes or cohorts of an uneven-aged stand differ widely in age (e.g., unbalanced), they are revealed as humps on the diameter distribution curve. The diameter distribution of each even-aged component broadens with age and will also be modified if the age class is composed of different species that grow at varying rates.

The most accurate assessment of the age-class structure of a stand comes from actual counts of annual rings. It is seldom reliable to depend on the criteria illustrated in Fig. 1 until direct age determinations have been made in representative stands typical of a locality. When such counts are made, consideration should be given to the fact

Box 3.3 (Continued)



Box 3.3 Figure 1 Typical examples of four different kinds of stand structures show the appearance of stands in vertical cross-section and corresponding graphs of diameter distribution in terms of numbers of trees per unit of area. The trees of the first three stands are all of the same species. The third comprises a multi-aged (three-aged) stand. The fourth stand consists of several species, but all of the same age. (DBH, diameter at breast height). *Source:* Mark S. Ashton.

that many species start as suppressed advance regeneration beneath older trees. In such instances, the effective age (i.e., the period since the trees were released) is more important than the chronological age. In other words, any core of fine growth rings around the pith is best discounted in assigning a tree to its proper cohort. With species in which this phenomenon is common, the number of annual rings at breast height is a good approximation of effective age if there is no tight core of rings at that level.

Differences in age distribution are most easily recognized in pure stands and in mixed stands composed of species with rates of height growth so nearly identical that the trees of a single cohort are aggregated into a single stratum in the crown canopy. However, even-aged mixtures of tree species usually segregate into different canopy strata and exist as **stratified mixtures** (Fig. 1) in which species of differing ecological status occupy different strata. The structure and development of these are considered later in this chapter.

classes) are almost always, in nature or through management, unbalanced with one dominating age class that is usually the youngest. Examples of unbalanced age distribution can include virgin old-growth stands and stands that have been partially cut without plan. Unbalanced uneven-aged stands are common and may be highly desirable, as long as they are recognized and treated for what they are. The term irregular is often used to describe unbalanced multi-aged stands of two to three age classes.

To summarize, the definitions of "even-aged" and "uneven-aged" remain similar to most interpretations by others (e.g., Nyland, 2016). The terms "cohort" and "effective age" are merged to define age, for silvicultural purposes, as the time of release or growth after disturbance and establishment. Three age classes (cohort classes) are used. These best broadly characterize the regeneration methods described in the book – single-age (even-aged); multi-aged (two to three aged, unbalanced uneven-aged); and all-aged (balanced uneven-aged). This follows the logic of Oliver and Larson's cohort classification (Oliver and Larson, 1996) but is more refined in defining age class than O'Hara's classification of multi-aged as anything more than a single age class (O'Hara, 2014).

Combining Differences in Age, Composition, Stocking, and Site to Define Stands

Species composition is another attribute defining stands. Identifying stand boundaries by species composition can be done by characterizing species change in stem density and basal area. In nature, species compositions change as a reflection of: (1) inherent differences in site quality

(a)

(b)

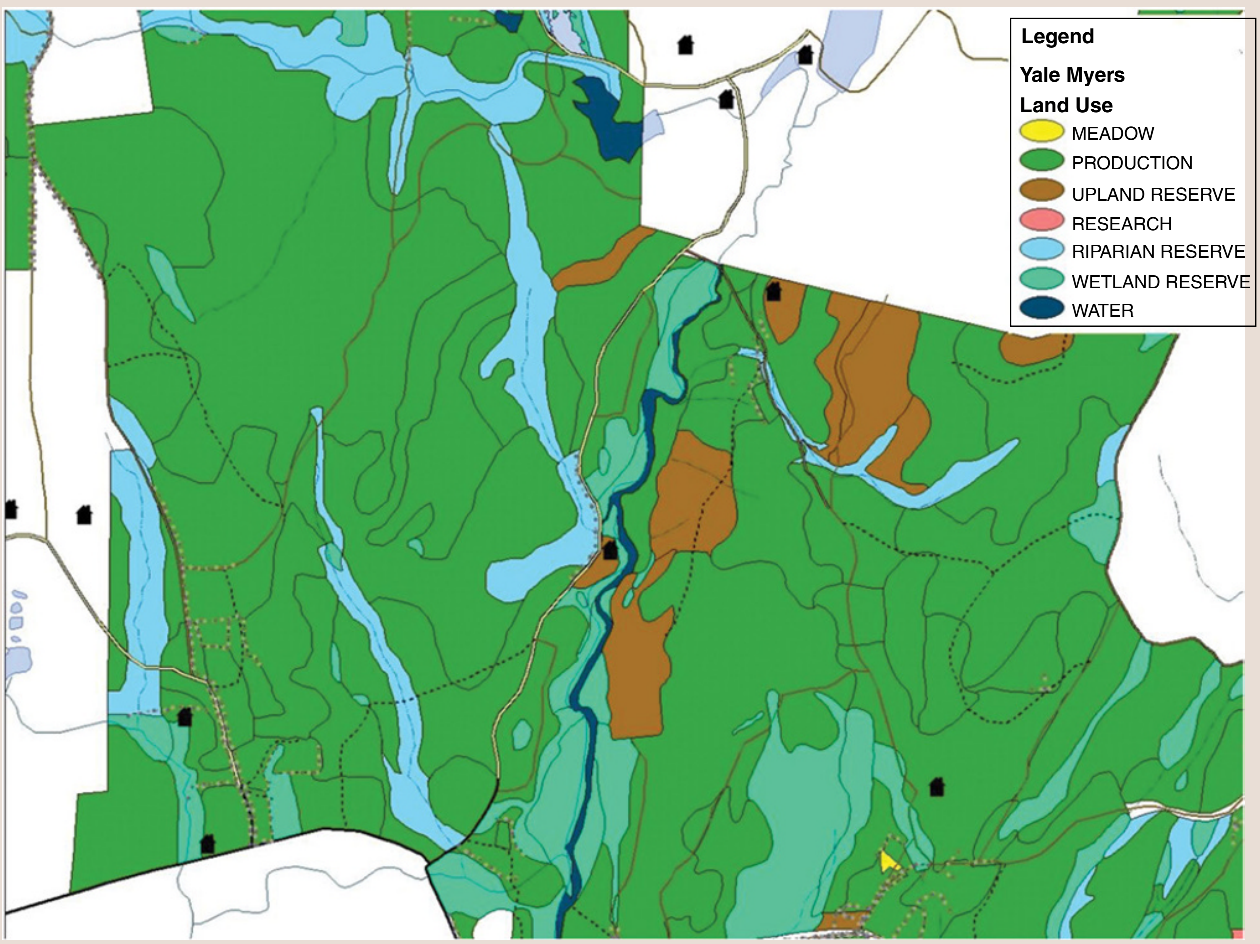
Figure 3.5 **(a)** A photograph of the foothills of the western Himalaya, India. Stands can easily be identified by marked differences in species composition across the topography. The drier spur ridges are dominated by a hard pine, *Pinus roxbughi*, while the slopes and gullies are dominated by evergreen oaks (*Quercus leucotrichophora*, *Q. floribunda*). *Source:* Mark S. Ashton. **(b)** An aerial depiction of the forest canopy and its variations in tree density, species composition, and age class across varying sites. The white lines in the foreground define various stands based on crown density and size, and species composition. Yuganskiy Nature Reserve, Siberian taiga, Russia. *Source:* Adapted from T. Bulyonkova, 2012 under the terms of the Creative Commons Attribution Share-Alike licence CC-BY-SA 2.

(site class) such as across a gradient of dry, moist, and wet topography; and (2) type of disturbance and the developmental stage of the stand (successional stage). Finally, differences in densities of trees (stocking) can also be used to define stands. In nature, densities are often different in one area as compared to another because of limitations in seed dispersal or because of competing non-woody vegetation such as ferns and grasses in some areas versus others. All these attributes taken together – age-class distribution, species composition and density, and variations in site quality and site classification – provide an integrated protocol for defining a stand (Fig. 3.5).

Since stands are the basic management unit for the application of silvicultural decisions and treatments, they are therefore the basic unit of land-use planning in forests. This requires the careful identification of stands for different social and management objectives. In some cases, management goals can be complementary, such as timber production and early seral wildlife habitat. Stands can have a number of compatible social values, but where management objectives are incompatible, stands need to be separate so decisions can be made to meet both objectives (e.g., protection of old growth and early seral wildlife habitat) (Box 3.4).

Box 3.4 The rationale and development of a stand-based land use map for the Yale-Myers Research and Demonstration Forest in northeastern Connecticut.

The core reserve design (Fig. 1) is built around the most ecologically and hydrologically sensitive sites comprising open and wooded wetlands and riparian forests that form a network of corridor-shaped stands throughout the production forest. Upland reserves comprise inaccessible ledges and areas of important upland ecological value. They are connected to the greater reserve area via the riparian reserve system. About one third of the forest is in some kind of reserve but this changes with the proportion of wetland/riparian area and steep and rocky slopes and ridges as compared to "workable" slopes and soils that are not sensitive to erosion and compaction.



Box 3.4 Figure 1 Stand-based land use map for the Plusnin and Curtis Divisions of the Yale-Myers Research and Demonstration Forest. *Source:* Yale School of Forestry and Environmental Studies.

New Developments in Landscape-Level Ecological Planning

Many researchers now argue that at the larger scales of landscape and physiographic region within which stands have been defined, the intensity of silviculture and forest management practice should emulate the disturbance cycles and the structure and composition of the original presettlement forest. Research has matured to develop a sufficient body of work that has been enough to define itself as "New Forestry" or "Ecological Forestry" (Kohm and Franklin, 1997; Seymour and Hunter, 1999; Seymour, White, and de Maynadier, 2002; Perea, Buse, and Weber, 2004; Long, 2009). However, this work has evolved in places where natural forests are extensive, human populations are low, and ownerships of such forests are large. These forest regions have strong public ownerships and influences such as Canadian Province lands and US National Forests of the sub-boreal, boreal, western temperate coastal, and intermountain regions of North America. There has been enough work now to merit changes in management of these forests to the degree that new regulations and statutes have begun to define management regimes that are first and foremost guided by benchmarks of spatial and temporal patterns of natural disturbance. These regulations consider landscape and regional-scale ecological factors as the first priority (Ontario Ministry of Natural Resources, 1996; British Columbia Ministry of Forests, 1995b). This means that economic and social considerations are constrained by overarching ecological goals of structure and function (Perera and Buse, 2004). This is unusual, and is the reverse of more populated forest regions. Forests that are more intensively utilized by people often comprise smaller or more fragmented private land ownerships with strong but contrasting social values. These forests tend to be driven first by economic and social priorities (e.g., agroforestry, urban, industrial, smallholder). The ecology and silviculture of a site are therefore viewed as constraining guides of what one can and cannot do. Both approaches can work but are obviously appropriate to very different circumstances and landscapes that are either human dominated or not so dominated.

The "ecological forestry" approach attempts to benchmark stand-level developmental processes of structure and age class to landscape-level spatial and temporal natural disturbance processes (Table 3.1). Such benchmarks gauge the natural range of variability in historic disturbance (Perera, Buse, and Weber, 2004). This is used to then define intensity and scale of silvicultural treatment and intrusion. The assumption is that this approach better attains the elusive nature and goal of sustainability – at least from an ecological perspective (Perera and Buse, 2004).

Table 3.1 Ecological attributes that can be measured to define benchmarks of natural forest pattern and process.

Disturbance attributes	Example of emulation criteria
Nature of disturbance	
Average rate for a large region and its variation	Fire-return interval, Hurricane return interval
Spatial pattern of variation	Spatial probabilities of damage (wind, fire, flooding)
Temporal pattern and variation	Intervals between fires, defoliation events, floods
Geometry	Size and shape
Consequences of disturbance	
Spatial and temporal patterns of composition	Patterns in residual vegetation, succession
Spatial and temporal patterns in age and structure	Patterns in age-class distribution

Source: Adapted from Perera and Buse, 2004

An example of an "ecological forestry" approach is the work on the northern hardwood–mixed conifer forests of northern New England and maritime northeast Canada. Based on long-term natural disturbance dynamics of windstorms, spruce budworm, and fires, researchers have developed disturbance comparability indices calculated for each stand, and a weighted average determined for various sized landscape units (Seymour and Hunter, 1999; Seymour, White, and de Maynadier, 2002; Maclean *et al.*, 2009) (Box 3.5).

Such developments in silviculture that emulate the scale and temporal dynamic of natural disturbance regimes of forests do not, unfortunately, negate the conflicting values of biodiversity conservation and timber production. New developments in ecology and conservation biology have provided a better understanding of the impacts of human uses on forests and the resulting effects on biodiversity. However, it still lies with the forester who must balance these directly conflicting values when managing for both, through wise resource allocation. One such conceptual approach to achieving multiple social goals in land use allocation is the **landscape triad** approach (Seymour and Hunter, 1999). To start with a simple example, a large forest area with multiple social drivers of conservation and utilization owned by a single private landowner can plan a stand network of ecological reserves for biodiversity conservation designed to counterbalance stands allotted to production forestry (e.g., timber). To enhance ecological robustness, the production forest stands and reserves would be embedded within a matrix of forest stands that are managed for both diversity and production using the principles of ecological

Box 3.5 Benchmark examples of disturbance and return interval metrics for: northern hardwood and mixed coniferous forests; mixed oak–hickory deciduous forests of northeastern America; and forests of the Pacific Northwest.

Northern Hardwood and Maritime Spruce–Fir Region of New England and Northeast Canada

Presettlement human impacts were local and restricted to settlements on shorelines, fertile valleys and floodplain soils, and along travel routes. They reached peak impacts between 1300 and 1600 AD. Here fire was used to promote oak, hard pines, berry production, and hunting. An estimated 1–2% of the forest was impacted by such disturbances in a chronic way, occurring every few years. The majority of the forest remained relatively untouched mesophytic beech, maple, spruce, and fir.

Post-settlement human impacts in the last 200 years have covered almost 100% of the region several times over, primarily through iterations of heavier and more extensive timber cutting by large industrial and small private landowners with progression in time, particularly starting with the industrial revolution (about 1870 onwards). Some of the best soils originally settled by Native Americans were cleared for farmland and much of this remains today. The more marginal lands reverted to second-growth northern hardwood over a century ago.

Natural disturbance impacts are primarily convectional windstorms 2.5–50 acres (1–20 ha) in size and varying with topography; ice storms, usually extensive in the 2500s of acres (1000s of hectares) but varying with elevation; insect outbreaks (variable in size) recurring at intervals of several decades that affected about 15–20% of the landscape over a 100-year period. Fire of natural origin was rare and was estimated to occur at intervals of 700–2000 years.

Mixed Oak–Hickory Deciduous Forests of Southern New England and New York, Southeast Pennsylvania and the Northern Piedmont

Presettlement human impacts were extensive across the region focused on swidden cultivation on the lower-lying, more fertile soils, and mast-nut and berry cultivation in the uplands. Disturbance through extensive and recurring fires promoted hickory, oak, and chestnut. Where fires or swidden agriculture did not occur, the forest would be dominated by beech, tulip poplar, and maple. Early settler records state much of the forest looked like a savannah woodland. Some extensive grasslands occurred through almost annual burning to promote game habitat, including the woodland bison.

Post-settlement human impacts are extensive with most of the region having been converted to sedentary subsistence agriculture starting 400 years ago. Much of the land was in poor pasture for domesticated livestock (sheep, cattle) and only a fraction was actually tilled for crop cultivation. Remaining lands remained in woodlots that were repeatedly cut. At its zenith, over 60–70% of the landscape was in some kind of cleared agricultural land. With the blossoming of global trade with the Industrial Revolution and the expansion of better lands to the west, most of the poorer land reverted firstly to pine (starting around 1850) that was cut over for the packaging/box industry (1890–1920), and which was then replaced with second-growth hardwoods comprising the disturbance-tolerant oaks, hickories, and chestnuts. The absence of fire and selective cutting has now largely promoted the conversion of these forests to maple, tulip poplar, birch, and beech. In addition, today's forests are impacted by a wave of exotic diseases and insects (e.g. chestnut blight, emerald ash borer, Dutch elm disease) and fragmentation from suburbanization.

Natural disturbance impacts comprise large episodic disturbances such as tornadoes and hurricanes regionally affecting approximately 250,000 acres (100,000 ha) that occur once in approximately 100 years for a given area, to convectional windstorms in 2.5–250 acres (1–100 ha) that can occur across landscapes every few decades. Natural fires are rare.

Coastal Forests of the Pacific Northwest

Presettlement human impacts were localized to burning the most fertile valleys that created small prairies and shrublands. Fires were used to increase wildlife forage and berries. These comprised mixed-severity fires that maintained Douglas-fir and hardwood brush and grasslands. Otherwise the majority of the forest comprised mesic old-growth western hemlock–Douglas-fir. Tribal groups practiced relatively primitive swidden agriculture, with a greater reliance on gathering fruits, fishing, and hunting. These activities promoted seasonal camp movements from the rivers to the uplands following the movement of animals and fish. Tribal groups in the Pacific Northwest had some of the most complex hunting and fishing societies in North America.

Post-settlement human impacts were widespread primarily from logging that started around 1850 with the building of lumber mills along Puget Sound. With the expansion of the railroads and new technology from the late 1800s to 1940, lumber companies could exploit much larger and formerly inaccessible areas. Today, no more than about 10% of the original old growth remains in the states of Washington and Oregon. Much of this was saved in the early 1900s with the formation of the US Forest Service and National Park Service and the acquisition of their respective lands. The best lands, however, remained in private hands that today still comprise productive and intensively managed Douglas-fir plantations.

Natural disturbance impacts comprised lightning strikes that increased with elevation and continued inland. Fires from these strikes were infrequent (at intervals of over 500 years), severe, and stand replacing. The long intervals of time between stand-replacing disturbances, together with relatively fertile young soils and high precipitation, promoted a mesic coniferous forest type that had some of the highest standing basal areas in the world.

Source: Adapted from Nowacki *et al.*, 2012.

Table 3.2 Conceptual allocation of land uses using the triad approach for three geographic regions across North Carolina: (1) Appalachian Mountains; (2) Piedmont; and (3) the coastal plain.

Land use category	Appalachians	Piedmont	Coastal plain
Urban/suburban	1%	5%	15%
Agriculture	5%	15%	25%
Intensive forestry (plantations)	5%	15%	30%
Low-intensive forestry (natural woodlands)	30%	50%	20%
Wildlands (parks)	59%	15%	10%

Source: Mark S. Ashton.

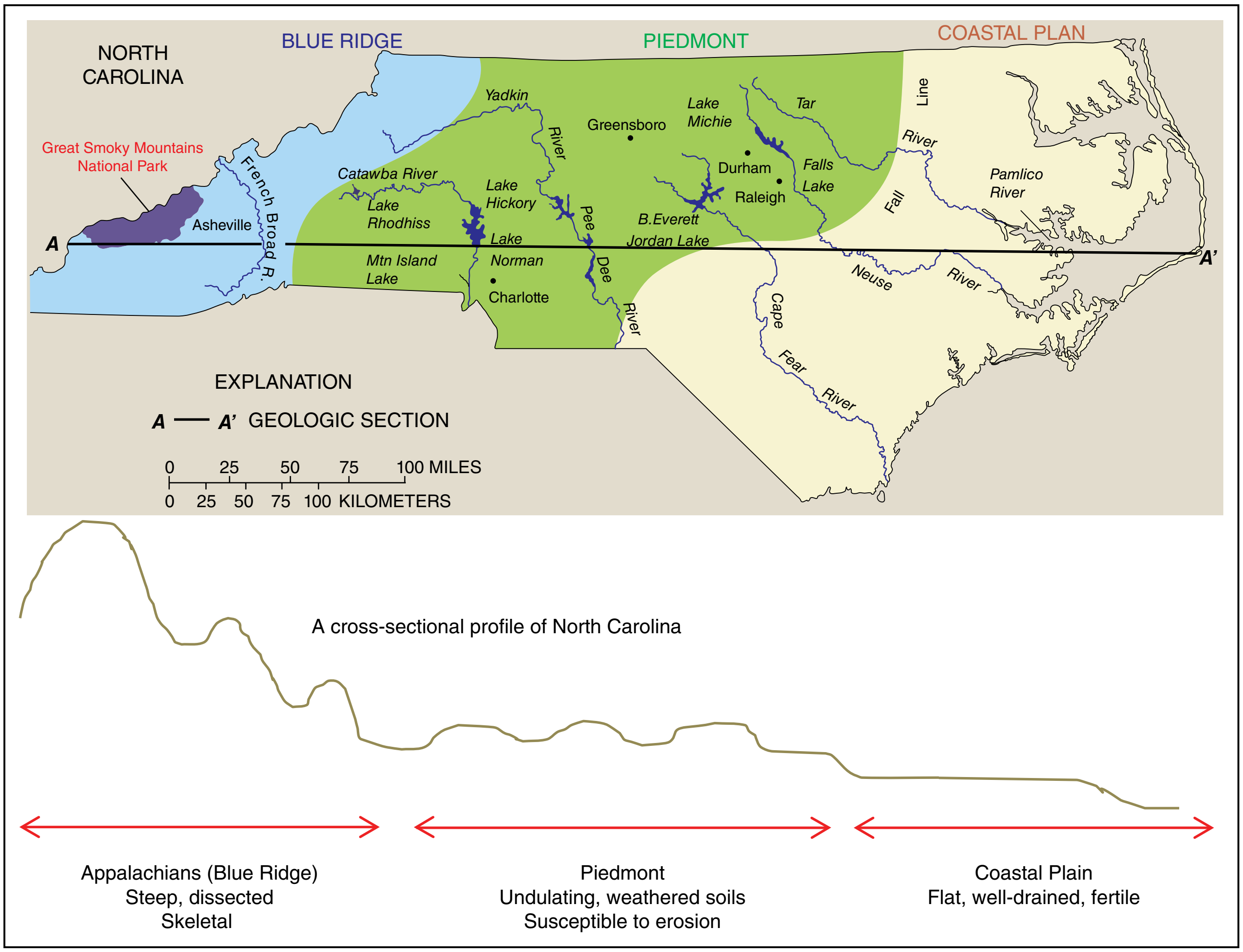


Figure 3.6 Map and cross-sectional profile of North Carolina (*A–A*) depicting the Appalachian Mountains (pale blue), Piedmont (green), and coastal plain (pale yellow) from west to east. *Source:* Mark S. Ashton.

forestry. The triad approach to land use allocation therefore identifies three types of land: (1) intensive commodity production areas; (2) areas with little or no resource use by people except low-intensity recreation; and (3) areas in which modest resource use is allowed while ecological values are carefully protected.

This approach is best applied to large landowners with extensive forest lands where timber production is desired, but other constraining values of biodiversity conservation must be met. Irrespective of whether the less intensive management of the land is called "ecological" forestry or an approach that treats the forest through longer rotations and natural regeneration methods, the idea of a land use that is largely extensive and serves to moderate the extremes of preservation through reserves and highly intensively managed lands for single commodity production is a good one. Such an idea is a conceptual land use allocation tool that can be transferred to regions in which most of the land is allocated to intensive commercial cropland where mandates can be made to allocate more toward reserve and unintensive mixed use. Such a mandate will likely increase the resilience of the landscape to sustain the productivity of commodity crops in the long run, through improved hydrology, soil productivity and biodiversity services of erosion control, flood mitigation, nutrient conservation, crop pollination, and biological control of pathogens and pests (Table 3.2, Fig. 3.6).

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4

Stand Dynamics: The Ecology of Forest Succession

Introduction

A forest stand may seem static but it is really a dynamic, ever-changing, living structure. After establishment, the choices made in silviculture are usually based upon altering stand-level processes (see description of defining stands in Chapter 3). **Stand dynamics** is the study of changes in forest stand structure over time, including stand behavior after disturbances (Reichle, 1981; Means, 1982; Oliver and Larson, 1996; Franklin *et al*., 2002). In practicing silviculture, a forester must be able to predict what kind of vegetation will follow regenerative disturbances, and what patterns of development should be anticipated in the vegetation as the stand grows older. This chapter introduces the different kinds of stands and their developmental processes.

The chapter first defines the basic kinds of initiating disturbances which can be categorized as lethal or release. It then describes the stages of stand development after initiating disturbances for single-aged or single-cohort stands. The use of age-class and cohort terminology is clarified for the purpose of this book and its application in silviculture. Using this terminology, the nature of canopy stratification and development is progressively described and defined, starting with single-aged, single-species stands, then single-species, two- or three-aged (multi-aged), and then single-species, all-aged stands. Mixtures are then treated first as mixed-species, single-aged stands, then mixed-species, two- or three-aged stands, and lastly mixed-species, all-aged stands. The final part of this chapter compares this terminology and description of stand dynamics with paradigms of forest succession by other ecologists.

Initiating Disturbances and Sources of Regeneration

All silvicultural procedures are, at least to some degree, simulations of natural processes in which stands start, develop, and are replaced, gradually or suddenly. No plant starts or accelerates its development unless something dies or is killed, which then provides the plant open growing space. Established plants often exclude others by expanding, suppressing, or killing weaker ones. Some plants can endure beneath taller neighbors and thus share growing space with them. Silviculture imitates and regulates the processes involved.

An important distinction can be made between disturbances (Fig. 4.1) such as: (1) fire that can be said to "kill from the bottom up" because they are more likely to kill small plants than large; and (2) windstorms or pests that kill more large trees than small trees, and thus "kill from the top down." The natural disturbances that initiate new stands from the bottom up can be categorized as **lethal** to the groundstory (Zhang, Pregitzer, and Reed, 1999; Harper *et al*., 2002; Winter *et al*., 2002). For example, some fires burn so hot that virtually all preexisting plant life is killed. The other major kind of disturbance that kills from the top down, has been categorized as **release** because these disturbances include insect outbreaks and windstorms, which destroy the upper canopy but allow the release of the understory (Worrall, Lee, and Harrington, 2005; Svoboda *et al*., 2010). Decisions about the regeneration of stands usually involve choices of the kinds of disturbance to simulate. See Chapter 5 for more details on the kind of disturbances and their relationship to the nature and origin of regeneration.

New trees can be recruited from many sources. Among these are seeds, nursery-grown plants, vegetative sprouts, and various forms of stored advance growth that have previously started beneath old stands (sources and processes of regeneration are described in Chapter 5).

Stages of Stand Development

After an initiating disturbance of any kind, trees of a single age class or cohort proceed from birth to death through a sequence of developmental steps (Oliver and Larson, 1996; Franklin *et al*., 2002; Franklin, Mitchell, and Palik, 2007). These must be recognized if

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

(a) (b)

Figure 4.1 **(a)** Fire-killed stand of lodgepole pine in western Montana. Natural regeneration of pines has started, and the fire eradicated the serious dwarf mistletoe infestation that caused the witches' brooms in the pines. *Source:* US Forest Service. **(b)** Stand of interior cedar–hemlock, British Columbia, that has been partially blown down by a convectional windstorm. *Source:* Mark S. Ashton.

understanding of stand dynamics is to be used to achieve management objectives by imitating, guiding, or altering natural processes in post-establishment silvicultural treatments (e.g., thinnings).

The first stage in stand development (Fig. 4.2) is called **stand initiation**. After a disturbance has created vacant growing space, the new trees that have become established in it (or preexisting larger ones that expand into it) do not fully occupy the space. Until they do, there is opportunity for additional plants to fill the empty spaces. Often, the plants that fill the newly vacant spaces are herbaceous annuals or other short-lived species that may come and go quickly.

Ultimately, both the aboveground and belowground growing space is filled with plants, mostly woody perennials in the case of forests. The tree crowns become closed in the horizontal dimension, and some of their lowest foliage starts to die because of shading by the upper foliage. This event starts the second stage of stand development, the **stem exclusion stage** (Box 4.1). During this stage, the trees start to compete with each other; the more vigorous ones encroach into the growing space of weaker trees that eventually die, usually from lack of light or soil moisture, in a process called **suppression**. Establishment of additional regeneration of tree species is also prevented.

Unless some disturbance wipes out the stand and starts a new stand initiation stage, an aging stand will gradually enter the **understory reinitiation stage** (Box 4.1). In this stage, scattered trees that have previously been successful in competition with other trees begin to be lost to pests, other damaging agencies, or cutting operations,

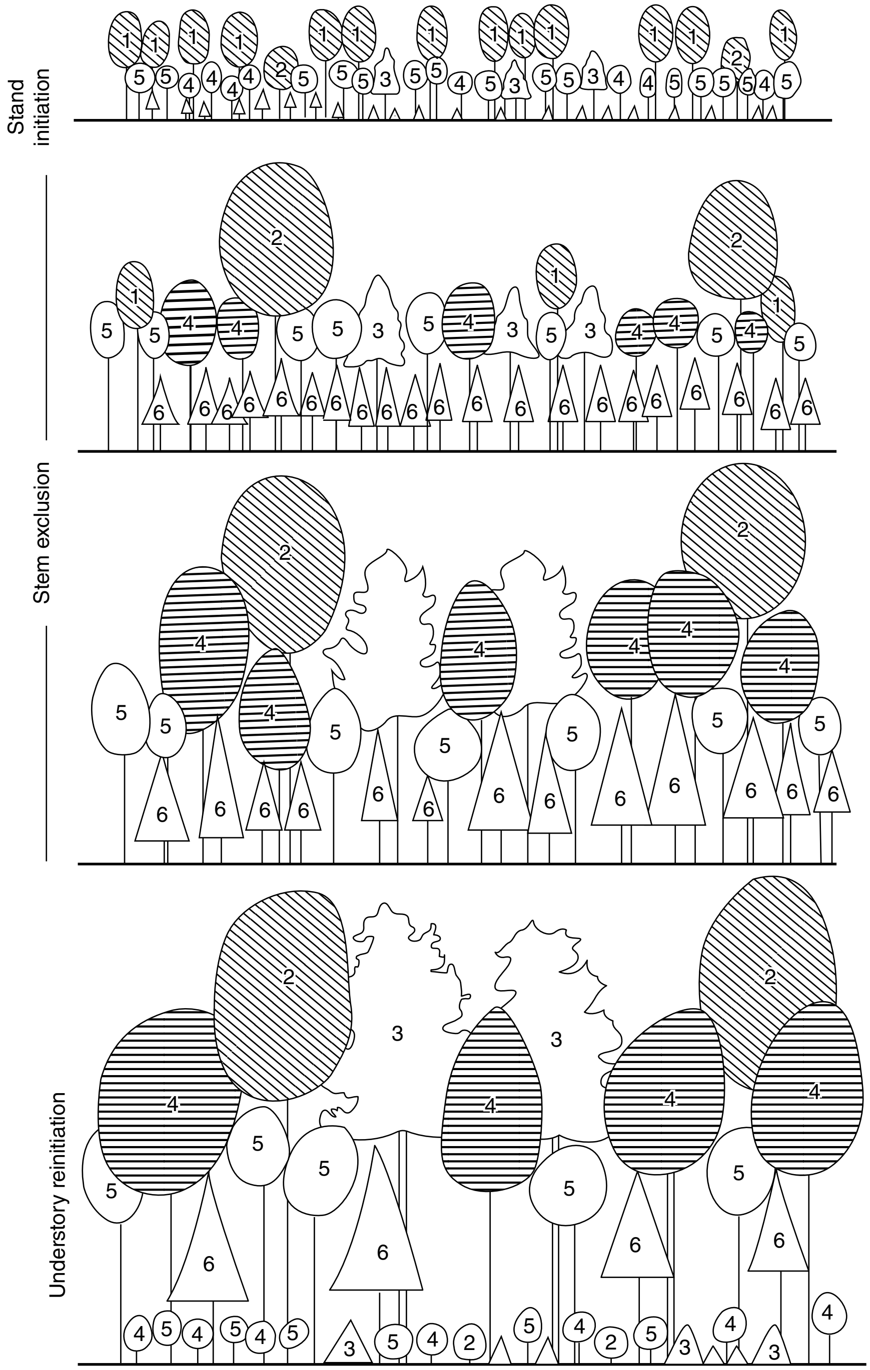

Figure 4.2 The same mixed stand at advancing stages of development, starting at the top with the stand initiation stage, then proceeding through the stem exclusion stage to the beginning of the understory reinitiation stage. Number and crown shapes identify the size of different species in the stand. Species: 1 – a short-lived pioneer that cannot tolerate shade after being over topped; 2 – a longer-lived pioneer that is a fast-growing emergent; 3 – a late-successional emergent with a delayed ascent to the tops of the canopy; 4 – a late-successional species with slow initial development that reaches the main canopy; 5 – a long-lived pioneer species with initial rapid development that is overtaken by species 4 but can withstand shade after being overtopped; and 6 – a very shade-tolerant late-successional species that usually remains in the lower strata. Figure 4.3 shows the same stand developing into old growth. *Source:* Yale School of Forestry and Environmental Studies.

Box 4.1 A list of physiological, morphological, and structural characteristics by the stage of stand development.

Stand Initiation

- **Environment**: an immediate release of soil nutrients, increased soil moisture, and dramatic increase in amounts of light. The more severe the disturbance, the more opportunistic the species regeneration strategy favored.
- **Growth morphology and stand structure**: annual and biennial grasses and herbs are favored first to temporarily occupy the site. Woody species favored are those that are fast-growing, with expanding crowns. In climates where moisture is non-limiting, crowns can be umbrella-shaped and expansive, and can act to competitively suppress other species below.
- **Physiology and leaf structure**: species with large leaves, high photosynthesis rates in full-sun, and with fine fibrous surface root systems that are superficial and laterally branched for maximum acquisition of nutrients and water.

Stem Exclusion

- **Environment**: growing-space becomes fully occupied with strong competition for soil resources and light.
- **Growth morphology and stand structure**: complete crown closure and competition. Promotes small compact crowns with monopodial stems that are fast-growing in height.
- **Physiology and leaf structure**: favors species with high photosynthesis rates per unit crown area with small, thick leaves to reduce water loss but maintain high rates of light capture per unit leaf.

Understory Reinitiation

- **Environment**: the maturation of the canopy trees and increased seed production, increased light, favorable changes in surface soil structure, and increased humidity and carbon dioxide can all potentially play a role in facilitating establishment of new vegetation.
- **Growth morphology and stand structure**: crowns become flat-topped. Root systems are surficial with disproportionately more growth allocated aboveground to light capture than belowground.
- **Physiology and leaf structure**: shade intolerant canopy leaves are small and the crown shallow cauliflower-shaped. Shade-tolerant leaves are large, planar in arrangement, and thin, to capture small amounts of light. Leaves are susceptible to desiccation.

Old-Growth

- **Environment**: heterogeneous availability of soil resources and light in the understory from small disturbances and canopy tree mortality from old age (insects and disease).
- **Growth morphology and stand structure**: spatially and temporally punctuated release and suppression of shade-tolerant species that established in understory reinitiation that over several cycles of canopy opening and closure can attain the forest canopy.
- **Physiology and leaf structure**: leaves and crown are plastic with abilities to change crown morphology through periods of suppression and release.

Source: Data from Oliver and Larson, 1996 and from Franklin *et al*., 2002.

and their crowns do not fully close again. The small vacancies thus created allow the establishment of new plants beneath the old stands. These are often advance regeneration of shade-tolerant species.

Unless something happens to replace most of the stand, the gradual process of death of overstory trees and replacement by younger age classes (depicted in Fig. 4.3) leads gradually into an **old-growth stage** (Spies, 2004) (Box 4.1). This stage commences when a majority of the original trees are gone and one or more of the new age classes or cohorts compose parts of the top canopy. It may continue on past the death of the last original trees. The number of different age classes increases, although it would be most unlikely that any balanced uneven-aged stands would come into existence without having been cut deliberately in order to create such an outcome. The stands would have many dead trees both standing and fallen. Under purely natural conditions, production of wood and other organic matter would tend to be balanced by losses to death and decay. The total number of species of plants may increase. Stratified mixtures typically develop, and foliage often extends from the ground to the top of the stand, at least in some parts of the stand. Franklin *et al.* (2002) go further in refining and describing several different stages within old growth that relate to the spatial complexity of structures and their developmental processes (see Box 4.1).

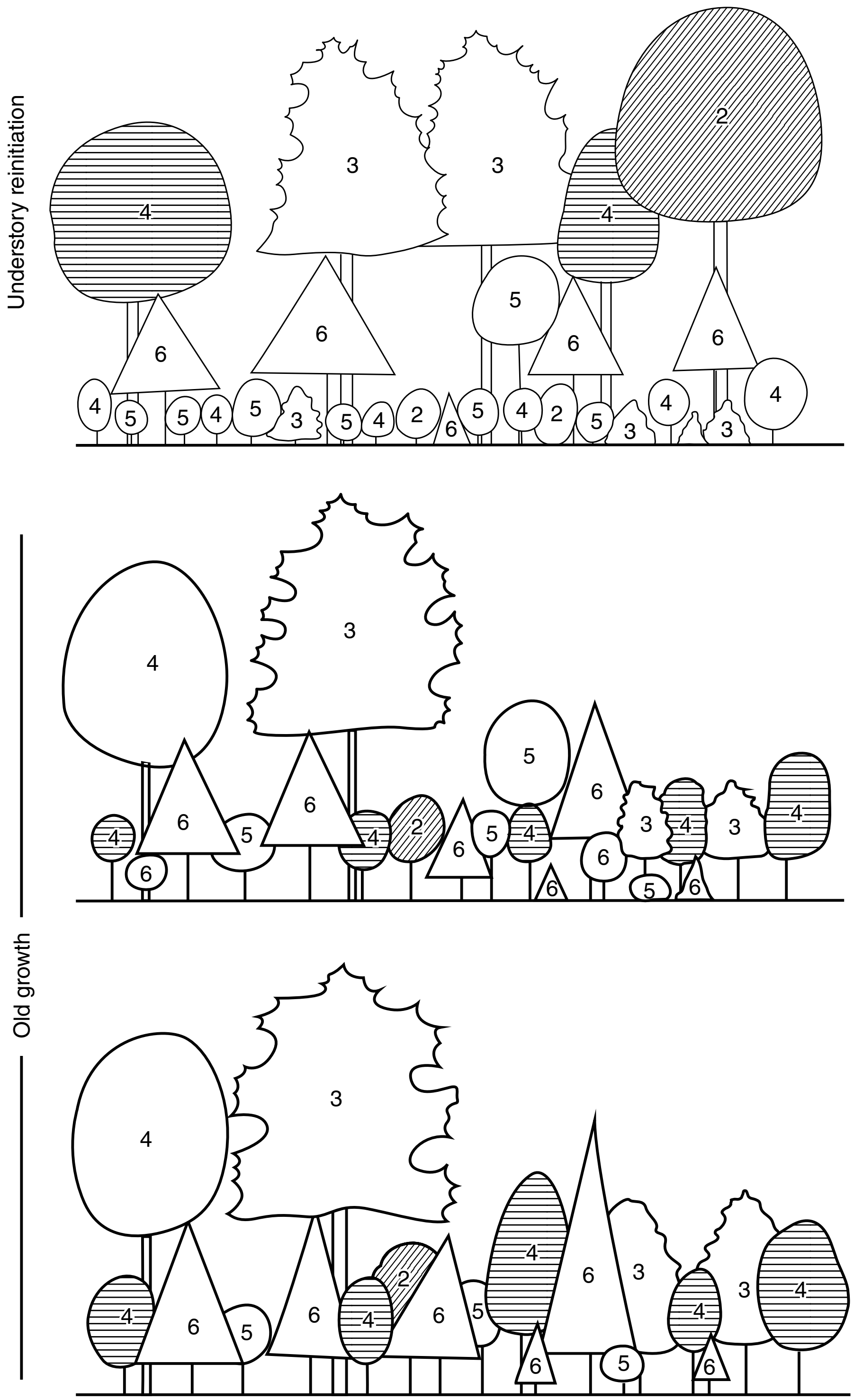

Figure 4.3 Continuation of the stand-development sequence of Figure 4.2, starting late in the understory reinitiation stage and extending into the old-growth stage. The five species have the same numbers as in Figure 4.2. Species 1 was too intolerant to become re-established in the understory. *Source:* Yale School of Forestry and Environmental Studies.

Defining Cohorts and Age Classes

For the purposes of planning for cuttings and for forecasting the future growth and yield of stands, it is important for foresters to assign ages to stands or parts of stands that have begun growth at different times in the past. The terms **cohort** and **age class** are used for dating the ages of stands. A cohort contains all of the trees that had been established at a specific time, usually following a forest disturbance. For example, if a stand was partially burned, killing half of the trees, the seedfall for next year's regeneration would likely produce enough seedlings to cover the entire stand. Those new seedlings would be called a cohort. However, if that stand had been burned so badly that only a few trees survived, it might take 30 years for the seedlings to become established across the stand. Even though there may be a span of tree ages from 1 to 30, these trees are also a cohort. The specific age is not important, it is the disturbance event that creates the new cohort.

Foresters tend to describe cohorts by disturbance type, date, and species. Some cohorts are well known. The 1988 Yellowstone fires burned vast areas and produced a huge cohort of young aspen across the landscape; the 1938 hurricane in New England blew down many stands and created a very large white pine cohort. Cohorts are also created in silvicultural operations, such as planting or shelterwoods. Cohorts can include mixed species, and foresters can even focus on just a particular species within a mixed stand, and treat it as a cohort.

If the range of ages of trees within a cohort is very narrow, it is often called an **age class**, rather than a cohort. The age-class terminology is often used when a stand is composed of trees that are all of the same age, so a stand could be described, for example, as a 5-year age class.

Cohorts and age classes are defined and their differences described in detail in Chapter 3. **For the purposes of this book, cohorts and age classes are treated as the same. It is therefore assumed that the effective age of a cohort at time of release is used for treatment application rather than its real chronological age**.

Defining Canopy Stratification by Age Class

Single-Species, Single-Aged Stands (Even-Aged)

Many ideas about silviculture are dominated by the view that all stands should be perfectly even-aged (single-aged) and of only one species. These stands are indeed very common. They typically arise in nature after lethal disturbances such as hot fires or, artificially, from programs of clearing and planting. Usually, the species composition remains pure only if soil moisture or some other site factor is so restrictive that only a single species can endure (Box 4.2).

During the stem exclusion stage, the trees of pure stands compete fiercely with each other, mainly because they all have crowns in the same stratum. The typical pure stand starts life with a relatively large number of small trees, usually thousands or tens of thousands/acre (hectare). The number of trees decreases as they grow larger, at first rapidly but more slowly with each passing decade. By the time the understory reinitiation stage starts, this number has been reduced to a few hundred trees/acre (ha) or to even less than 100.

Box 4.2 Examples of North American stands of different disturbance origin and age-class.

1) Single-species, single-aged stands: lodgepole pine of the interior west and jack pine in the boreal after a severe and widespread lethal disturbance.
2) Single-species, two- or three-aged (multiple-aged): western larch of the Rocky Mountains that has originated after sub-lethal severe fires that are widespread but spatially variable promoting the establishment of spatially clumped cohorts and the survival of older individuals.
3) Single-species, all-aged: pure eastern hemlock of moist temperate northern hardwood forest that has recruited over a long period from frequent periodic small wind and ice storms that open up the canopy.
4) Mixed-species, single-aged: recruitment and release of a single cohort after a heavy single cutting of all stems in a mixed-species oak–hickory stand.
5) Mixed-species, two- or three-aged: an old-field pine stand of the eastern hardwood forest type, with occasional older "wolf tree" oak and sugar maple that were shade trees of the original pasture. A third cohort can establish if the pine is partially harvested, allowing the younger progeny of the "wolf trees" to move into the canopy.
6) Mixed-species, all-aged: an old-growth Douglas-fir/western hemlock forest of the Pacific Northwest that has multiple openings of varying sizes that originated from different canopy disturbance events promoting the release of intimate mixtures of tree species growing at different rates.

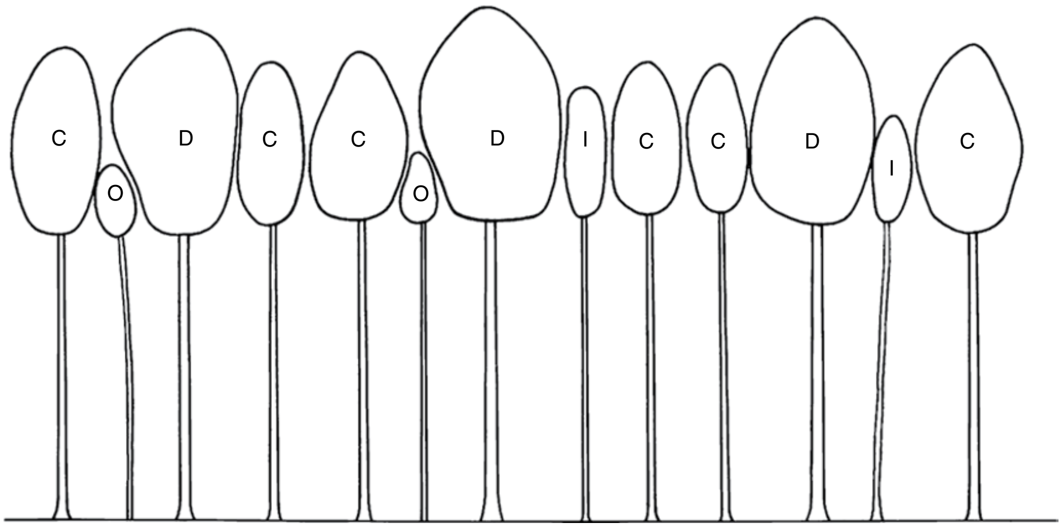

Figure 4.4 The Kraft Crown Classification (Kraft, 1884). The relative positions of trees in different crown classes in a single-aged (even-aged), pure stand. The letters D, C, I, and O denote dominant, codominant, intermediate, and overtopped crown classes, respectively. E, denoting an emergent crown class, is not depicted. *Source:* Kraft, 1884.

This continual reduction in numbers is the result of competition and rigorous natural selection, and is the expression of one of the most fundamental biological laws of silviculture. Those trees that are most vigorous or best adapted to the environment are most likely to survive the intense competition for light, moisture, and nutrients. Growth in height is the most critical factor in competition, although the trees that increase most rapidly in height are almost invariably the largest in all dimensions, especially in the size of the crown. As the weaker trees are crowded by their taller associates, their crowns become increasingly misshapen and restricted in size. Unless freed by random accidents or deliberate thinning, these trees gradually become overtopped and ultimately die. In this constant attrition, the weaker members of an age class are progressively submerged, and the strongest forge ahead. Very few trees ever recover a leading position after they have fallen behind in the race for the sky. This process is called **crown differentiation**. The relative crown positions of trees within this differentiation process can be categorized into classes (Figs. 4.4, 4.5). Five crown classes are generally recognized. This classification of tree crowns is called the Kraft Crown Classification, after the nineteenth-century German forester who devised it. It is useful only for single-species stands, or for stands composed of different species with identical regimes of height growth. The five classes are as follows.

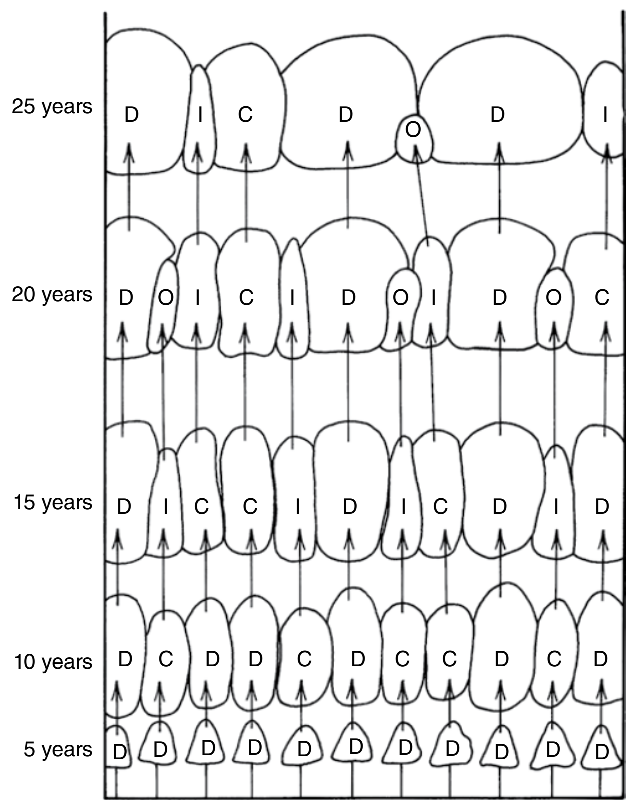

Figure 4.5 The process of differentiation into crown classes as a result of competition in a pure, single-canopied, single-aged stand, showing how some trees that were initially dominants may lose in the race for the sky. *Source:* Yale School of Forestry and Environmental Studies.

- **Emergent**: trees with crowns extending well above the general level of the canopy so much so that the bottom of the crown is above the canopy.

- **Dominant**: trees with crowns extending above the general level of the crown cover, and receiving full light from above and partly from the sides; larger than the average trees in the stands and with crowns well developed but possibly somewhat crowded on the sides.
- **Codominant**: trees with crowns forming the general level of the crown cover and receiving full light from above but comparatively little from the sides; usually with medium-sized crowns more or less crowded on the sides.
- **Intermediate**: trees shorter than those in the two preceding classes but with crowns extending into the crown cover, formed by codominant and dominant trees; receiving little direct light from above but none from the sides; usually with small crowns considerably crowded on the sides.
- **Overtopped**: trees with crowns entirely below the general level of the crown cover, receiving no direct light either from above or from the sides. Synonym: "suppressed."

This qualitative classification is simple and can be applied without measuring heights or crown widths. The intermediate and overtopped classes are well defined and easily distinguished from the two superior categories. However, it is difficult to draw a sharp distinction between the dominant and codominant classes. It would be desirable if the codominant class, which usually includes the majority of the main canopy trees, could be objectively subdivided into vigorous and less vigorous categories. Anything growing in a stratum that is definitely below the main crown canopy should be thought of as part of the understory, rather than as a part of the overtopped crown class. The development of pure, even-aged stands is presented in more detail in the introductory chapters on methods of regeneration (Chapter 6) and thinning (Chapter 21). True clearcutting and coppice methods of regeneration often develop single-species, single-aged stands (see Chapters 8 and 12) (for examples see Box 4.2).

Single-Species, Two- or Three-Aged Stands (Multi-Aged)

It is possible to have stands in which a new cohort or age class starts beneath an old one that is entirely or partially eliminated, allowing the new one to continue its development. Natural fires may create such stands (Box 4.2). They can be of pure- or mixed-species composition. Chapter 11 describes the use of irregular shelterwood and seed-tree regeneration methods in establishing these kinds of multi-aged stands. If the stands are pure, each new cohort develops with the same differentiation into crown classes (described in the previous section).

Single-Species, All-Aged Stands

When small gaps are created in stands by cutting or destructive events, new cohorts (age classes) may start to develop in the small openings. The creation and development of such all-aged stands, as discussed in Chapter 13, is easiest to understand if they are first thought of as pure stands without the complications found in mixtures of species (Box 4.2). The development processes of the little pure groups of trees that constitute pure uneven-aged stands are essentially the same as those of pure even-aged (single-aged) stands, except where the older groups interfere with the younger groups where they meet at their interfaces. Natural stands of this kind, both balanced or unbalanced in age-class distribution, most commonly exist in habitats where soil moisture deficiencies or occasional fires allow only one tree species to grow. Many ponderosa pine forests of the western interior epitomize this condition (Fig. 4.6). Most all-aged stands are actually mixtures of species.

The management of uneven-aged stands is complicated even if they are pure, especially if attempts are being made to mold them into self-contained sustained-yield units. These efforts usually involve manipulation of diameter classes and efforts to create reverse-J-shaped diameter distributions. The management of these stands is much less complicated where the trees and groups of trees are thinned to enhance growth, and harvested when mature without attempting to change age-class structure. These treatments involve what is aptly called the selection method of regeneration and are considered in much more detail in Chapter 13.

Mixed-Species, Single-Aged Stands

Unstratified Canopies

It is possible, but uncommon, for two or three species of the same age to grow in height at the same rate for long periods. If they do, they can be thought of, and managed, in the context of the single-canopied structure almost as if they were pure stands (Guldin and Lorimer, 1985). Ordinarily, however, one species tends to suppress its associates; very small differences in height growth become greater as the leaders forge ahead and the laggards suffer. For example, this can happen in mixtures of loblolly pine and shortleaf pine; loblolly pine generally gets ahead, unless dry site conditions cause loblolly pine to slow in growth. In central Europe, mixtures of the tolerant species beech, spruce, and fir must be thinned constantly to keep the beech or spruce from exterminating the fir. In fact, trees that drop out of the single-canopy stratum are usually eliminated or are promoted into the upper canopy by release operations (see Chapter 20 on release operations).

An additional concept about stand development patterns of single canopies relates to the fact that different

Figure 4.6 An all-aged stand of ponderosa pine in southern Oregon, after a group of mature trees has been removed to make a vacancy for establishment of regeneration. *Source:* US Forest Service.

species grow at different rates. Often, mixed stands are mosaics composed of little pure stands arising from a small, pure patch of young trees. Because each patch develops independently (except at the edges), it is possible for each species to grow at its own rate. A process can be postulated in which each patch might be reduced to a single tree in a mixture that became stratified in some late stage of development. Patch-wise mixtures of this kind are most likely to arise from deliberate planting, usually in squares. Patchy variations in soil or microenvironmental conditions may cause them to start from natural seeding, but the randomness imparted by seed dispersal and other factors usually causes species to be intermingled.

Stratified Canopies

Single-aged stratified mixtures develop when different species represented by advance regeneration, sprouts, new seedlings, or combinations of the three, start off together upon release by some major disturbance such as a windstorm, insect outbreak, or heavy cutting. Although these mixtures are usually thought of as originating from natural regeneration, they can also start with the planting of mixtures of species.

The developmental processes of stratified mixtures of species are different from those of simple pure even-aged (single-aged) stands or cohorts. There is differentiation of tree heights into horizontal canopy strata or stories, one above the other, with one species or a group of similar species in each stratum. Note that this kind of differentiation is not simply dividing into Kraft crown classes within a single canopy stratum; it is dividing within various canopy strata of many species.

The sorting into strata begins in the stand initiation stage (Fig. 4.7) and becomes most pronounced in the stem exclusion stage. Competition is most intense among trees within a given species and stratum, but the lower strata are not excluded by the upper ones. The species of the lower strata are adapted to survive there without participating in the race for the sky that characterizes pure, single-canopied stands. The species that arose to the top of the total crown canopy during previous forest generations generally do so again, even though this development may not take place until the later stem exclusion stage is well underway.

The species groups of each stratum differ from the other groups in the rate of height growth, tolerance of shade, rooting depth, and similar ecological characteristics (Fig. 4.8). It is rare that any two associated species grow in height at precisely the same rate throughout life, even when they are not actually competing with each other. If they are intimately intermingled, the species with the most rapid rate of juvenile growth in height will gain ascendancy over the slower-growing species, which will lag even farther behind because of the lack of light beneath the canopy.

In the simplest kind of stratified mixture, each species ultimately tends to occupy a different stratum of the total crown canopy. In general, there will be as many strata as there are groups of species that differ from one another in height growth and tolerance. The stratification is not always perfect or readily apparent. Even when the stratification is well differentiated, a few individuals of a species that goes with one stratum may by chance have grown upward into a higher stratum or have been left behind in a lower one. Furthermore, the observer

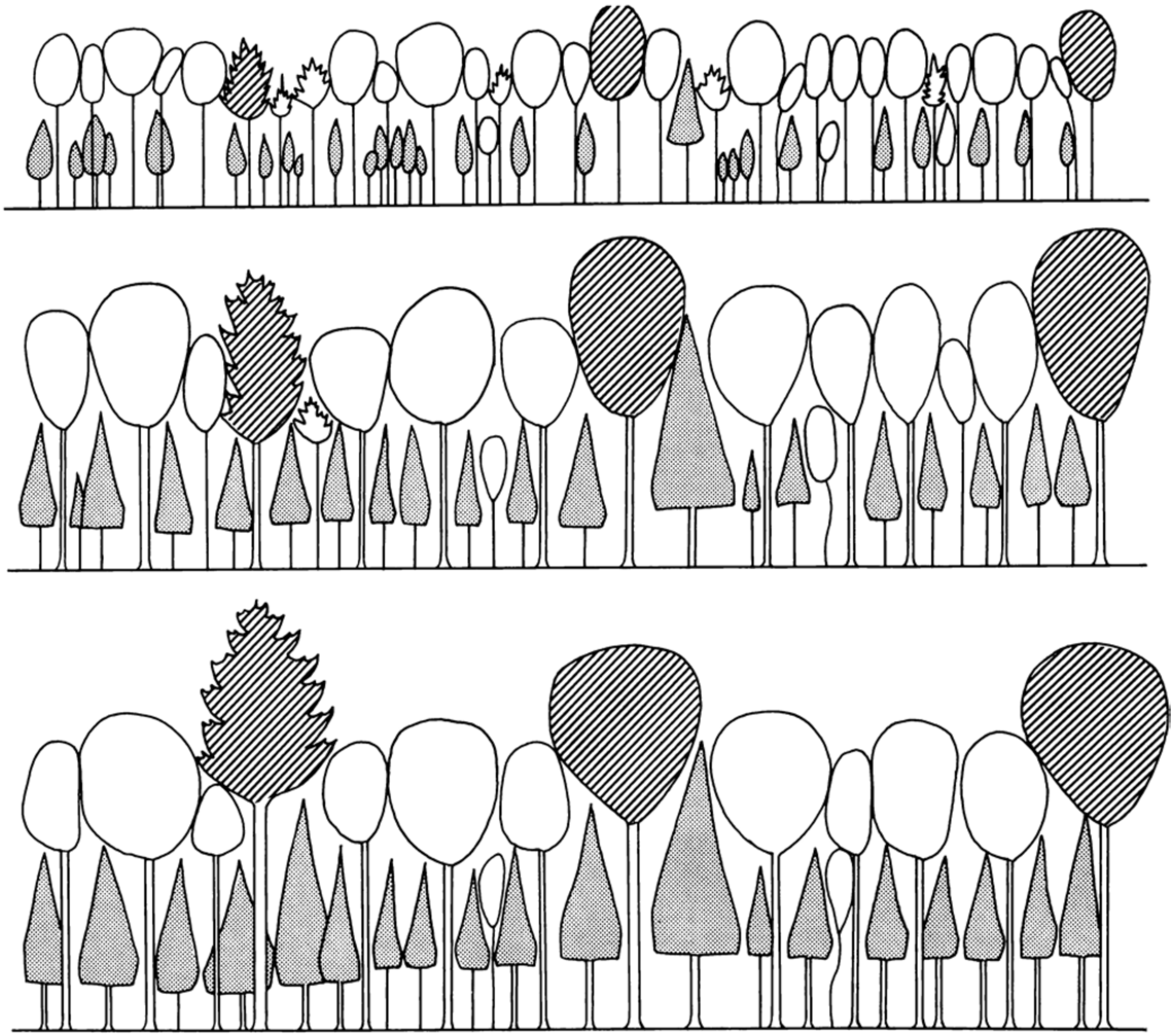

Figure 4.7 Stages in the natural development of an untreated stratified mixture in an single-aged stand of the eastern hemlock–hardwood–white pine type. The upper sketch shows the stand at 40 years with the hemlock (gray crowns) in the lower stratum beneath an undifferentiated upper stratum. At 70 years (middle sketch) the emergents (hatched crowns) have ascended above the rest of the main canopy, except for the white pine, which has only started to emerge. The lower sketch shows the stand as it would look after 120 years with the ultimate degree of stratification developed.*Source:* Yale School of Forestry and Environmental Studies.

standing beneath a stratified mixture will have to look closely and exercise some imagination to perceive the different strata. Stratified mixtures have been widely reported on throughout North America, specifically: western US (Cobb, O'Hara and Oliver, 1993; Deal, Oliver, and Bomiann, 1991); eastern US (Oliver, 1978; Kelty, 1989; Fajvan and Seymour, 1993).

The different strata can be designated A, B, and C downward, a terminology first applied in the forests of the moist tropics, where the concept of the stratified mixture originated (Fig. 4.9). The A-stratum may be continuous, but is more often composed of scattered, isolated emergents that either grow faster or continue growing longer than their associates. Sometimes the emergents are simply called "emergents" and then the A-stratum is regarded as the highest fully closed canopy layer. Each stratum can also be designated by the name of the most characteristic species within it, as when a pure Douglas-fir stratum is above one of pure western hemlock, or an oak stratum is above a sugar maple stratum, which is above beech.

An understanding of the structure and development of stratified mixtures provides a way of dealing with many kinds of complex stands. These are usually found where soil moisture and other site factors are so favorable that many species can grow, although they can also occur on less favorable sites. On sites that contain many tree species, it is very difficult to maintain pure, single-canopied stands. Frequently, a single species is not capable of fully

Figure 4.8 A single-aged mixture of northern hardwoods, about 90 years old, in the Adirondack Mountains of New York. The emergents are the white pines at the left, and some white ashes in the middle, which are still nearly leafless in this spring picture. Sugar maples and yellow birches form the main canopy stratum with American beech in the understory stratum. *Source:* Yale School of Forestry and Environmental Studies.

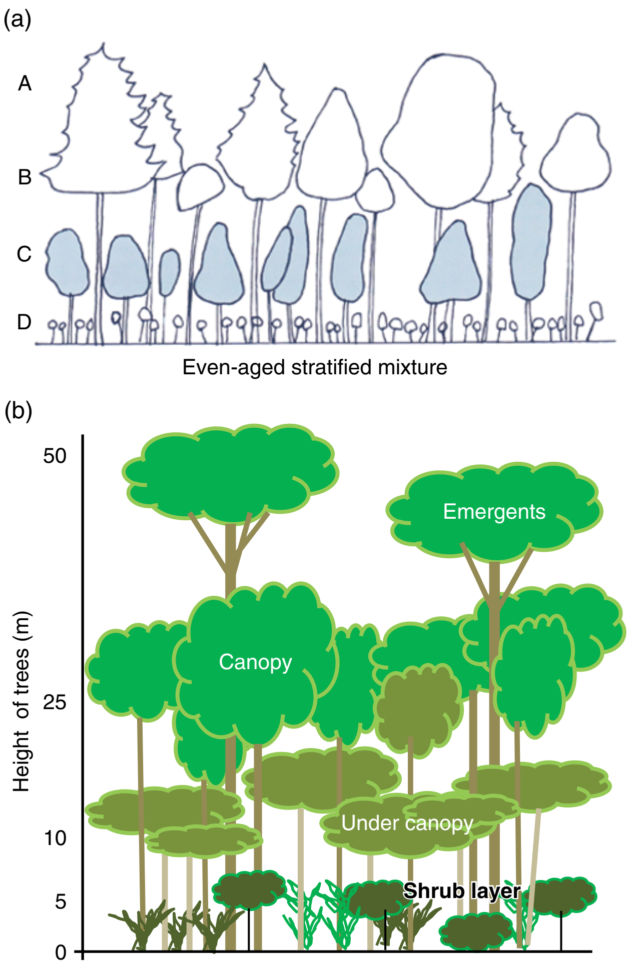

Figure 4.9 Two different categorizations of forest strata. **(a)** A single-aged, mixed-species, stratified stand showing four strata: A – canopy, B – subcanopy, C – understory, and D – groundstory. *Source:* Yale School of Forestry and Environmental Studies. **(b)** A second-growth tropical rainforest as an example of a single-aged mixture with the following strata: emergent, canopy, under canopy, and shrub layer. *Source:* Mark S. Ashton.

occupying such sites, and stands turn into stratified mixtures unless costly treatments are applied to reduce the invaders.

If the soil factors are not seriously limiting, the vegetation collectively intercepts more of the photosynthetically active light than a pure stand of some shade-intolerant upper-stratum species (Kelty, 1989). The vertically distributed foliage in a stratified mixture represents a sequence of sun- and shade-leaves that are more fully adapted to do this, than the rather similar array of leaves within a single species. However, in some habitats the lower stratum species can be undesirable or not permanently adapted to the site, and so a single species would be better adapted. For example, the exclusion of fire on some dry, fire-prone sites has sometimes allowed the establishment of lower-stratum species that cause excessive buildup of forest-fire fuels, or might rob the upper stratum of water, causing growth decline of the desirable species.

Plants follow many different strategies for exposing their leaves to solar radiation and claiming growing space. Most annual plants are designed to expend all of their carbohydrates on herbaceous roots and shoots that fill a small amount of growing space quickly, with no provision made for woody stems and roots, and none for the future except for seeds. Perennial herbaceous plants tend to develop enduring control of small amounts of the soil space, but avoid investing substance in the woody stems needed for races toward the sky. Trees and other woody perennials have a wide variety of strategies. Shrubs invest so little in building sturdy stems that the sizes of their crowns are limited. The stems of woody vines are designed almost entirely for conduction of water and dissolved substances.

Most pioneer tree species have weak stems that are designed to expose large amounts of foliage to sunlight rapidly. Usually, they either collapse of their own weight

when young or are overtaken by species with stronger stems that start height growth more slowly. However, some quick starters, such as yellow-poplar and some hard pines, continue height growth for long periods and dominate the top stratum for whole rotations (see Chapter 5 for a more detailed description of functional grouping of species by kind of regeneration and growth strategy). It should be noted that every tree species has a limiting total height, greater on good sites than on poor, which should guide decisions about how to handle mixtures of species.

Many ideas about silviculture are based on the view that all useful species of trees grow quickly and steadily in height for whole rotations, but this is not true. A large number of tree species grow very slowly in height, or do not even grow in height at all, until they have built root systems that are adequate to supply water to the crowns (e.g., longleaf pine, oaks). When that is completed, the young trees can initiate rapid height growth, if growing space is available. However, if these trees have not been released from taller trees, they may remain stunted, but retain the potential for rapid growth for many years or even decades. Also, there is the interesting situation in which some shade-tolerant species may grow fairly rapidly in height for a time, but then lapse into very slow growth after being overtaken by faster-growing species (e.g., hemlock).

As a result of these phenomena, there can be remarkable reversals in the position of different species in the different strata. Northern red oak, for example, grows at a steady, moderate rate that cannot be accelerated; after several decades, associate species such as red maple and black birch that had previously gone ahead, then slow down and lapse into the lower strata (Oliver, 1978). Some species, such as the white pines and spruces (Fajvan and Seymour, 1993), may linger below the top of the canopy and ultimately emerge above it, simply because they survive or continue growing in height longer than their associates.

Stratified mixtures were first recognized by Richards (1952) in the wet evergreen and moist deciduous tropical forests, which are practically incomprehensible without this means of analyzing their structure. The fact that stratified mixtures can be even-aged has been learned in the temperate zone where trees have annual rings (Kelty, Larson, and Oliver, 1992). From these, it has been possible to reconstruct the patterns of height growth that lead to whatever structural arrangement exists at any developmental stage (Oliver, 1981). The myriad of such patterns that must exist in moist tropical forests is almost unknowable until ways are invented to determine ages of the trees. In one case, Terborgh and Petren (1991) were able to reconstruct the development of stratified mixtures in a datable series of even-aged stands that became established annually, as new soil was laid down while a tropical river shifted its course sideways each year. Even-aged stratified mixtures are now a very important legacy of land clearance and then recolonization after agricultural abandonment. Native mixtures of second-growth forests now comprise the majority of forest across Eurasia and North America (Whitney, 1994). Even-aged second-growth forests are also becoming an important forest type across Latin America, where agricultural lands are reverting back to brush and early second-growth (Wright, 2005; Chazdon *et al*., 2009).

Efforts to apply the Kraft Classification of crown dominance to stratified mixtures usually cause confusion about the past and future development of individual trees without adding much that is useful to tree description. However, trees of the same species do compete strongly with each other (Kittredge, 1988), and sometimes the different crown classes can be discerned within a stratum.

Although the lowest strata of shrubs (understory) or herbaceous vegetation (groundstory) are usually not counted among the woody stem strata, they may play an important role in the total structure and function of the forest ecosystem. These herbaceous strata are very common, even beneath stands of single tree species that are casually thought of as absolutely pure.

In mixed stands, stem diameters tell little or nothing about ages when different species are being compared. A slender tree of a C-stratum species may be as old as or even older than a large emergent of another species above it. Large gaps in diameter distribution within a species normally denote truly different age-classes. It is common for stratified mixtures composed of a single cohort to have varying degrees of the J-shaped diameter distribution that would be a plausible indicator of the balanced, uneven-aged structure if the trees were all of the same species. In such cases, the different diameter classes generally represent species with different schedules of height growth rather than different age classes.

The species of even-aged stratified mixtures are ordinarily arranged with intolerants in the upper strata, with species of increasing tolerance in each successively lower stratum (Fig. 4.8). There may be more than one species in a stratum. The order of vertical arrangement of species is not necessarily the same at all stages or ages. Not only do some species drop out, but also some may even exchange their positions. Some intolerants race quickly ahead but soon slow down and die (e.g., paper birch); other intolerants grow rapidly and steadily, and live on to old ages (e.g., ash, yellow-poplar, Douglas-fir). The more shade-tolerant species almost always start slowly and accelerate later (e.g., oak). The very shade-tolerant ones may endure as practically dormant seedlings or saplings and then shoot for the sky, but only when there is a gap

in the canopy (e.g., hemlock). Some species grow rather rapidly at first and then slow down and lapse into the understory (e.g., red maple). In other words, in mixed-species stands, the stand development is clearly *not* like that of a pure even-aged stand.

Collectively, the various strata often fill the growing space so long, that the stem exclusion stage may extend for long periods of time. Even if one of the upper layers is completely eliminated, a lower one will usually take over any vacant space. If there are no major lethal disturbances, vacancies gradually develop in the lower strata; the understory reinitiation stage starts and ultimately leads into a very complex, uneven-aged, old-growth stage.

Mixed-Species, Two- or Three-Aged Stands (Multi-Aged)

This text considers mixed-species stands that have two or three age classes to be multi-aged. These kinds of stands almost always have an unbalanced age-class distribution that is heavily skewed toward the youngest age class. This age class has regenerated from the most recent stand-initiating disturbance. These kinds of stands are very common in most forest types, particularly where large episodic disturbances occur that are sublethal, allowing some trees and species of the original stand to survive. Examples are numerous and include variable crown fires, large and violent wind disturbances, heavy but incomplete cutting, and smallholder land-clearance practices where trees are left for shade or economic value and then when the land is abandoned a young forest grows up around them. Such stand age-class distributions perhaps dominate most regions and forest types of North America (Oliver, 1981; O'Hara, 2014).

Mixed-Species, All-Aged Stands

Mixed stands with a history of partially effective or patchy forest disturbances develop into complex mixtures of species, fragments of stratified mixtures, and varieties of age classes or cohorts (Fajvan and Seymour, 1993). All stages of stand development are likely to be going simultaneously in some part of the stand. If there are truly different age classes or cohorts, there will be real variations in the height of the top of the main canopy in different parts of the stand. If shade-intolerant species that are normally found only in the upper strata exist in very different diameter classes within a stand, the stand is very likely to be composed of more than one cohort.

Where site conditions produce mixed stands, this chaotic kind of structure is characteristic of undisturbed old-growth stands. The same is true of **high-graded stands** from which the best trees have been cut, except that the best species and largest trees may have already been eliminated in an earlier cutting.

The intermingling of trees of very different ages often obscures and complicates processes by which different species sort themselves into different strata. Older individuals of species normally found in some lower stratum often reach the uppermost levels and the stands become irregularly uneven-aged. The best silvicultural solution for managing such stands lies in diagnosing the processes taking place in each separate part and treating it accordingly. Even though they may exhibit some semblance of a J-shaped curve for diameter distribution, they almost never approach the balanced all-aged condition. That condition is actually artificial; it is created by deliberate silvicultural action and not by random events of nature.

Old-growth forests that are mixed-species and all-aged are usually in forest types where return intervals between large disturbances are very long (>250 years), and where late-successional tree species that attain the canopy die from individual small events (e.g., windthrow, lightning strikes, pathogens, insect defoliation). Such forests are found in everwet climates outside of the hurricane or cyclone regions. Examples of mixed-species, all-aged, old-growth forests have been illustrated as profile diagrams in the older literature describing the floristics of primary (undisturbed) tropical rainforests in Southeast Asia and the Amazon (Fig. 4.10).

Relationship of Stand Dynamics to Other Interpretations of Vegetational Development

Compared to the paradigm of stand dynamics, there are other interpretations of vegetation change over time (Shugart, 1984; McIntosh, 1978; Cattelino *et al.*, 1979). The concept of natural succession formulated by Clements (1936) once dominated American ecology. An oversimplified version of this concept holds that pioneer vegetation of an initial **Stage 1** colonizes an area from which all preexisting vegetation has been eliminated. **Stage 1** soon dies and is replaced by a **Stage 2**, which is composed of other species that start under **Stage 1** and are relatively shade tolerant (Fig. 4.11). Ultimately, **Stage 2** is similarly replaced by **Stage 3**, and there may be additional stages leading to a stable, endlessly self-replacing stage called the **climax**. The originator of the concept made it far more complicated and sophisticated, but many of the disciples have oversimplified it.

Climax vegetation has been regarded by some as an ultimately perfect state of nature in which all organisms are represented and all physical and biotic factors are in perpetual balance. It was once postulated that this perfect condition required freedom from disturbance, although it has been conceded more recently that

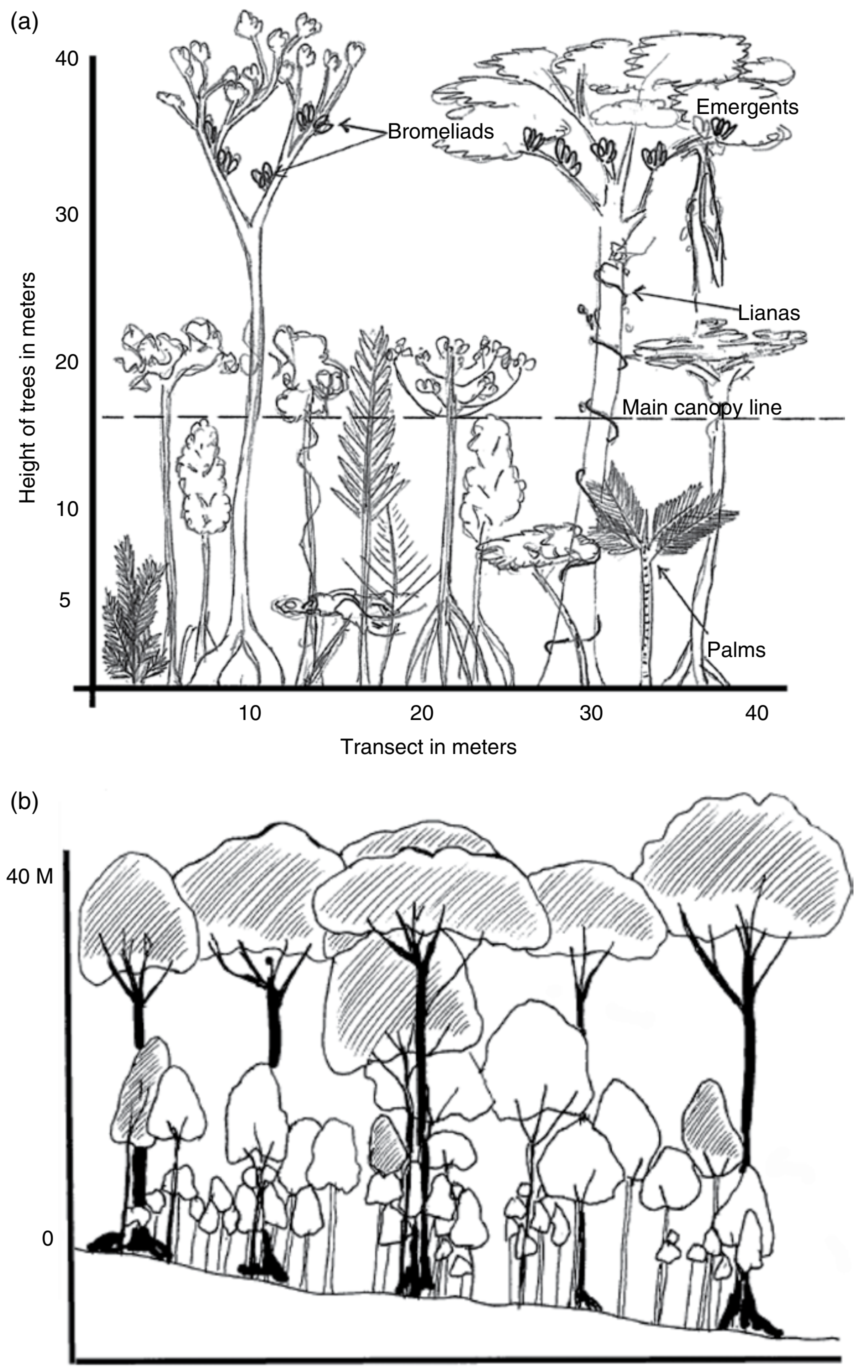

Figure 4.10 Profile diagrams for rainforests. **(a)** French Guyanan rainforest dominated by slow-growing late successional leguminous trees. Trees with bold outlines depict canopy and emergent species. The dotted line denotes the canopy layer and above. *Source:* Adapted from Richards, 1996. **(b)** A mixed dipterocarp forest growing on fertile soils in Sarawak. The canopy is less broken with few emergents and a dominance of mixed dipterocarp tree species in the canopy (darker shading). *Source:* Adapted from Ashton, 1964. For scale, 10 m is about 33.3 ft.

perpetuation of the essentially uneven-aged state depended on the occasional creation of small gaps in the growing space. In fact, the terms **gap** and **patch dynamics** have been coined to describe the study of patterns of establishment and subsequent development of vegetation in all vacancies of any size in the growing space (Pickett and White, 1985). In this sense, the term **forest stand dynamics** as used in this book is a kind of gap or patch dynamics, except that gaps or patches filled by single cohorts are called stands.

The Clementsian natural succession model does describe at least the early stages of development after most vegetation has been killed by severe disturbances, but it does not cover other sequences very well. According to the stand dynamics principles proposed by Oliver and Larson (1996), the stages of stand initiation, stem exclusion, and understory reinitiation represent early stages of the natural succession just described, and the old-growth stage covers all of the subsequent steps leading to the climax stage.

Figure 4.11 Successional development in which an old senescing stand of western larch in western Montana is dying and being replaced by subalpine fir and a few Engelmann spruce. *Source:* US Forest Service.

Enthusiasm for the simple Clementsian concept of natural succession and the climax stage as the sole pattern of vegetational development has declined, mainly because of two things. First, it was observed that fires and other major disturbances were so common, even in nature, that in many localities, the theoretical climax vegetation never had time to develop. Second, it became apparent that more complex ideas were necessary to account for the behavior of intimate mixtures of species and the effects of disturbance that killed only some of the plants growing in a unit of space.

The concepts of stratified mixtures and the principles of stand dynamics covered earlier in this chapter represent attempts to deal with the effects of partial disturbances and the interaction of different species. Each of the individual strata of a single-cohort stratified mixture often represents one of the sequential stages envisioned in the Clementsian concept of succession, with the species of the earliest stage being those of the A-stratum.

Some ecologists have applied the term **initial floristics** to the simultaneous appearance of many different categories of plant species in what is here termed the stand initiation stage. These ecologists call Clementsian succession **relay floristics**. The members of a single cohort that develop into a stratified mixture arise through initial floristics. Each one of these terms describes one of the various ways in which vegetation develops; the two concepts are complementary rather than conflicting, because each fits a different disturbance pattern. Relay floristics usually fits developments following disturbances such as hot fires that wipe out nearly all of the vegetation. Initial floristics is associated more with regeneration from sprouts and advance growth as well as new seedlings that start development following an initiating disturbance by wind or other agencies that kill stands from the top downward (see Chapter 5 for further details).

Another way of viewing stand development over time emphasizes the accumulation of biomass and chemical nutrients after a destructive regenerating disturbance. This perspective is very much a biogeochemical one (Bormann and Likens, 1981). The regeneration step is called **reorganization**, the buildup of biomass is referred to as **aggradation**, and the state in which the accumulation of biomass and nutrients comes into equilibrium with losses is the **steady state**. These stages are analogous to steps of stand initiation, stem exclusion, understory reinitiation, and old growth that relate to changes in tree populations.

There is no single universal pattern; in fact, there are more patterns than terms to describe them. In managing any category of stands, the forester should know as much as possible about their past and future development. It is good to be wary of preconceived ideas about standard patterns because there are more developmental sequences than are described in this book. Oliver and Larson (1996) cover this topic in more detail.

Choice of Developmental Patterns

Silvicultural choices can be thought of as determining what kind of stand developmental process or stage of natural succession is most desirable in a given situation.

In the Pacific Northwest, for example, the forester must often decide whether to perpetuate pure stands of Douglas-fir, or allow them to be succeeded by stratified mixtures of Douglas-fir, western hemlock, and redcedar. In the Lake Region, the choice may be between the pioneer aspen association and a climax stage such as the spruce–fir association. In the southeast US, decisions must be made about whether to let old-field stands of loblolly pine revert to pine–hardwood mixtures. In almost every kind of forest, it must also be recognized that some wildlife species may depend on stands that have some dead trees and other features of old-growth stands.

Several generalizations of wide, but not universal, application may be introduced at this point. In the first place, the most valuable commercial species tend to be relatively intolerant but comparatively long-lived trees representative of the early or intermediate stages in natural succession. Species such as pines, Pacific Coast Douglas-fir, yellow-poplar, and white ash definitely fall in this category. It is no coincidence that intolerant species are important commercially because they are the ones most likely to lose their lower branches through natural pruning. It is of significance that some of them are adapted to reproduce mostly after major disturbances that happen infrequently. If these are to survive from one major disturbance to another, they must be long-lived; as a result, they are likely to develop the economically desirable attributes of large stem size and resistance to decay.

Late-successional forest types, characterized by species such as hemlock, true firs, and beech, are frequently composed of branchy trees that produce less valuable wood. Because of their shade tolerance, they can reproduce almost continuously; thus the ability of individuals to endure for long periods is not so crucial in the survival of the species. Many pioneer species have even less capacity for individual longevity. However, they usually exhibit good natural pruning, and the necessity that they grow rapidly to seed-bearing age is an economically desirable attribute, although they usually have weak wood of low density.

Natural succession proceeds most rapidly and vigorously on the better sites, that is, on soils that are both moist and well aerated. It is sometimes impossible to resist the invasion of additional species without expensive silvicultural treatments. Furthermore, good sites are hospitable to the growth of so many species that silvicultural treatment becomes complicated and difficult. These considerations often have the paradoxical effect of making silviculture most efficient on sites of intermediate quality where uncomplicated stands can be maintained without strenuous effort. In fact, on poor sites occasionally it may be virtually impossible for succession to proceed beyond an intermediate stage, which is sometimes referred to as a **physiographic climax**. For example, pure stands of jack pine or red pine occasionally represent valuable physiographic climaxes on certain dry, sandy soils in the Lake Region.

It has been claimed that late-successional or old-growth types may be more resistant to, and more cheaply protected from, fire, insects, fungi, wind, and weather than earlier stages. In those cases where this advantage exists, it results more from the diversity of species and age classes than from age or position in the successional scale. Similar advantages sometimes prevail in mixed stands with a variety of age classes that are still typical of earlier successional stages.

It is often postulated that natural climax or old-growth communities are in a stable and favorable equilibrium with the physical and biological environment. Perfect stability and complete favorability do not exist, so it is in terms of relative degrees of each quality. For example, the balance achieved by long-continued natural processes, operating more or less at random, is not necessarily more favorable to the trees than to the organisms that feed upon them. The more artificial dynamic equilibrium produced by prudent silviculture may be less stable but ought to be more favorable from the standpoint of the integrated effect of all socioeconomic factors. If the dynamic equilibrium created by treatment ultimately balances at some disastrous condition, the silviculture was hardly prudent.

The naturalistic doctrine of silviculture did not arise from any clearly demonstrated disadvantages of early or middle stages of natural forest succession. It developed largely from disappointments with attempts to create unnatural types, particularly with exotic species or native species not adapted to the sites involved. In more recent times, it has been advanced as a result of concern for wildlife diversity and the need for conservation of natural areas.

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5

Ecology of Regeneration

Introduction

Even trees do not live forever. The time comes when they are cut or are naturally replaced by new ones. The world also has extensive areas where reforestation is needed to remedy the effects of previous misuse or natural accidents. Care must also be taken in managing new or regenerating forests. Young vegetation is so adaptable that what is done during the period of regeneration or establishment determines most of the future development of trees and stands. What happens in the first few weeks or months can shape the future composition and structure of a forest more than even the most heavy-handed subsequent silvicultural treatments. Many of the successes or failures of silvicultural treatments are determined during stand establishment. As the wise silviculturalist Professor David M. Smith always said: “Physicians can bury their worst mistakes, but those of foresters can occupy the landscape in public view for decades.” The ultimate act of regenerating a stand is so crucial that it should be kept in view throughout the whole rotation.

This chapter first describes how natural disturbances, driven by climate and the underlying geology and soils, have shaped vegetation over millions of years. It defines differences in disturbances and processes of regeneration establishment. Next, it describes the microsite environment and its four critical physical components: light, temperature, water, and nutrition. Then the stages of reproduction are described: flowering, seed supply, seed dispersal, seed storage, germination, and growth and establishment. The requirements for establishing natural regeneration based on knowledge of site and stages of reproduction are also described. Then the different kinds of regeneration adapted to different climates and their different disturbances regimes (fire, wind, and water) are categorized. Finally, an ecological framework and methods for thinking about, and imitating, natural regeneration processes and their plantation analogs are provided.

Ecological Role of Natural Disturbance

Trees evolved many millions of years before humans. Each species evolved adaptations to the natural disturbances under which they occur. The natural vegetation of any locality is a variety of species, each adapted to colonize some microenvironment or ecological niche that might become vacant and is at least barely favorable to plant growth (Grubb, 1977; Huston, 1979; Chesson, 2002). Evolution has produced lichens that can grow on bare rocks and epiphytes adapted to crevices high on the boles of standing trees. It is through this collective versatility that vegetation is able to approach full occupancy of the growing space. It is seldom a question of whether there will or will not be vegetation, but only of what kind.

Kinds of Natural Regenerative Disturbances

Natural vegetation ultimately arises after the occurrence of one of the many kinds of disturbances that, taken together, include a spectrum of intensities. It is necessary to know which species appears after what disturbance event. Disturbances can be categorized into two kinds that broadly represent either end of the intensity spectrum. The two categories have very different and profound influences on the composition and structure of forest regeneration: **lethal disturbance** and **release disturbance**. The understanding of natural regeneration processes has changed over this last century from one that was thought to be largely driven by small continuous disturbances leading to gradual changes in forest structure and compositions (Clements, 1916), to episodic large-scale disturbances triggering extended periods of recuperation and growth (Egler, 1954; Bormann and Likens, 1979; Oliver, 1980; Turner *et al*., 1998; Franklin *et al*., 2002). Both lethal and release disturbances play important roles in current thinking about regeneration dynamics. This section will start with discussing the most severe lethal natural anthropogenic disturbances and progressively address less severe ones.

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

Lethal Disturbances

Geological erosion events constitute the most severe kind of natural disturbance. In ecological terms, the only true primary succession starts with landslides, the melting of glaciers, or the formation of new land by water, wind, or vulcanism. Human-caused erosion or earth moving can also expose soil parent materials that are free of organic matter and deficient in nutrients.

The true **pioneer** vegetation adapted to colonize these vacancies created by these geologic processes is more likely to be herbaceous than woody plants, but there are some tree species, such as the true poplars, alders, willows, and certain river sandbar species, that can also establish without some initial herbaceous stage. Ordinarily, trees do not start on such barren surfaces until some other vegetation has begun to build up the organic matter or provide enough shade for tree seedlings to endure microclimatic extremes.

In silviculture it is seldom wise to simulate such drastic disturbances deliberately. However, foresters are often called upon to establish forests on parent material that has been exposed by erosion, road building, strip-mining, or similar events. This very difficult form of silviculture works best if there is a very clear idea of how natural pioneer vegetation develops on similar sites. Natural regeneration sources of such pioneer species must be seeds that are spread by wind, water, or animals.

The next most severe natural disturbance are the very hot fires that burn large amounts of dead fuel created by blow-downs or pest outbreaks, or which occur during extreme droughts and thus can burn as both deep ground fires, affecting organic soils, and canopy fires (referred to as "stand-replacing fires"). Lesser kinds of forest fires, even crown fires in living stands, are fueled mainly by the unincorporated organic matter of the forest floor, but usually do not consume all of the organic material and often have a patchy distribution in the live canopy layer. However, if there are large quantities of dead combustible material on the ground and on dry organic soils, fires can burn so hot that they can be almost as lethal as a landslide. The main difference is that most of the incorporated organic matter in the surface mineral soil remains intact.

The most severe fires usually eliminate most sprouting species, thus leaving the site nearly vacant for establishment of new vegetation from seed. The subsequent ecological successions are usually thought of as secondary ones because the remaining organic matter enables some species to start earlier than they would otherwise.

The significance of severe fires for silviculture is their similarity to artificial disturbances. Intensive cultivation and the complete removal of the original vegetation for arable agriculture, pasture, and certain kinds of silvicultural site preparation also leave only bare soil with incorporated organic matter and without woody perennials capable of sprouting. It is noteworthy that many illustrations of discrete, orderly, sequential stages of plant succession used in North America (see section on relay floristics below) come from the natural revegetation of agricultural lands abandoned during a century-long period that is coming to a close. The pure conifer stands that represent a stage in these old-field successions are so productive that they have been perpetuated in some regions (e.g., the northeast with eastern white pine, and the coastal plains and the Piedmont of the southeast with loblolly pine) as a silvicultural legacy of that epoch. The silviculture that simulates these cases depends on either natural seeding or planting of species adapted to colonize completely vacant areas.

Much of the prior paragraphs paint a fiery picture of what can be called "scorched-earth silviculture." This term is not intended to be demeaning because so many forests were and are regenerated in nature by fire (Fig. 5.1a). The tree species involved usually grow rapidly as individuals, probably because early attainment of seed-bearing status is crucial to their perpetuation and the fires are likely to be frequent. There are important economic advantages in having trees that grow rapidly in diameter and height, regardless of how well they produce strong wood. These species are very important in silviculture, especially in cases where large initial investments are made in planting.

Other examples of severe disturbances can be related to water. Severe floods from very heavy rains or huge snowmelts can bring fresh deposits of silt and sand that can be as much as several feet (meters) deep. Mudslides caused by volcanic activity that melts huge amounts of glacial ice from an exploding mountain can scour mountain valleys to the bedrock and re-deposit material in huge plains further downstream. Consequently, the mortality of plants following severe flooding and mudslides can be comparable to the other lethal disturbances mentioned above, although the scale in terms of areal extent is often less.

Releasing disturbances

The other general category of regenerative disturbance is from wind or from pests of large trees that kill forests from the top downward, but resulting in little ground disturbance, and sparing most plants of the lower strata (Fig. 5.1b). The species that are adapted to such circumstances are those with foliage constructed and displayed in ways that make the trees tolerant of shade. Their seedlings are usually not adapted to exposed microclimates, and their juvenile growth is slow.

These species can endure for many years as advance regeneration (in the form of small seedlings in the understory beneath old stands) and retain the capacity to initiate rapid height growth whenever some event releases them (Ashton, 1992a). Some endure as stunted seedlings

(a)

(b)

Figure 5.1 **(a)** A very hot crown fire as an example of a lethal disturbance. Nothing survives. **(b)** A large hurricane as an example of a release disturbance. The groundstory and root systems survive. *Source:* **(a, b)** US Forest Service.

and saplings, and others, as perennial rootstocks that survive while their tops grow up and are repeatedly killed back. Once released, most of these species maintain height growth for long periods. This characteristic, combined with the ability to maintain deep canopies of shade-tolerant foliage, can lead to long-sustained periods of high per-acre (hectare) production. However, such species tend to be limited to sites and regions that are continuously moist enough to reduce exposure to fire or drought stress. At risk of over-generalization,

they can be thought of as "advance-growth-dependent" species, best regenerated naturally under some sort of protective cover.

Disturbance regimes in this category include all sorts and scales of wind-caused disturbance from the very violent, large, and episodic kinds such as tornadoes and hurricanes affecting 2500–250,000 acres (1000–100,000 ha), to convectional windstorms affecting 2.5–2500 acres (1–1000 ha) that are often more frequent but still episodic, to multiple and single-tree fall events creating 250 ft^2 to 2–2.5 acres (100 m^2 to 1 ha) canopy openings that can often be almost continuous, but are usually seasonal and small scale (Franklin *et al.*, 2002; Ulanova, 2000). Wind can also interact with temperature such that on high-elevation slopes of mountains, trees can die in lines (fir waves) from exposure to desiccating cold dry winds. Also, where fire, ice, and water (flooding) events are frequent, and often predictably periodic (seasonal), vegetation exposed to such events is often pre-adapted to be destroyed or to experience dieback aboveground but then subsequently resprout from the roots systems that survive. Tidal zones, riparia, and fringes along waterways that flood predictably and frequently, savannas and woodlands prone to frequent creeping groundstory fires, and high mountain chutes prone to avalanches all promote vegetation to develop adaptive mechanisms to respond vegetatively in this manner. Finally, insects and pathogens can have significant killing and dieback effects on the forest canopy in all manner of scale depending upon the general or specific nature of the insect or disease and the degree of diversity of the forest composition.

Initial Floristics versus Relay Floristics

It is now very apparent that where vegetation has evolved with natural disturbances over millions of years, regeneration adapations demand that vegetation re-establish almost immediately post disturbance. This would be defined as **initial floristics** (Fig. 5.2a) (Oliver, 1980; Oliver and Larson, 1996; Turner *et al.*, 1998). This would make sense given the fact that species would have co-evolved with climate and disturbance to such a degree that their reproductive adaptation to securing a new growing space would be nearly immediate. Thus it is an accurate generalization to state that where forests and woodlands are exposed to disturbances of the same type and range of variability as that of their past, regeneration of forests is dominated by initial floristics (e.g., hurricanes in the eastern forests or fires in the west).

However, where forests and woodlands have been exposed to new disturbance regimes, species' reproductive traits (e.g., seed dispersal, microenvironmental germination requirements) may well be maladapted to the new conditions. In such cases, it may take a period of time where only the species most adapted to the new disturbance regime or environment (often different species from the original flora) will first establish. Only when environments or disturbance regimes become more amenable and similar to the original ones do species of the former forest start to grow. This is referred to as **relay floristics** (Fig. 5.2b) (Oliver and Larson, 1996). Relay floristics is often associated with anthropogenic disturbance impacts on forests. For example, relay floristics will occur where a lethal disturbance created by people from land clearing and intensive agriculture has

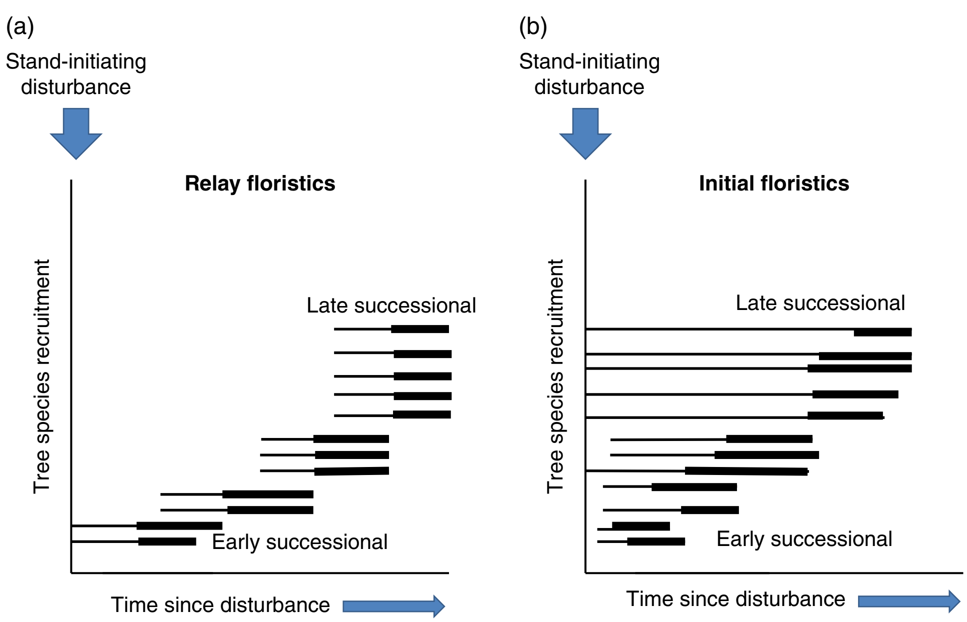

Figure 5.2 Graphics depicting the time of establishment, growth, and survival for tree species over successional time for **(a)** the relay floristics model, and **(b)** the initial floristics model. The lines depict the period of establishment and growth of a species. The thicker bars depict the period of canopy dominance. *Source:* **(a, b)** Adapted from Oliver and Larson, 1996.

been imposed upon a forest strongly adapted to regenerating after release-type disturbance. Relay floristics can also be associated with abnormal natural disturbances. For example, relay floristics will happen after a lethal mudslide or volcanic eruption occurs within a forest adapted to wind storms and tree falls.

Disturbance and the Environment of the Microsite

Irrespective of the fact there are big differences in kind, type, and frequency of disturbance that can largely be based upon lethal versus release level regeneration processes, new plants germinate and live through the most dangerous weeks of life within tiny worlds not more than several inches (centimeters) in any dimension (Fig. 5.3). The most important factors that determine survival and initial growth are therefore the environmental conditions of these small microsites. If these conditions are favorable, it makes no difference whether the spots are in the middle of a huge clearcut area or are the result of thinning. Seedlings respond to water, light, carbon dioxide, chemical nutrients, and biotic influences that make up their particular environment, regardless of the name of the silviculture treatment.

As far as initial establishment is concerned, a surprisingly small number of suitable microsites may suffice to regenerate a large area. The establishment of 2000 desirable seedlings per hectare theoretically requires only that 2000 suitable spots are distributed over the hectare. If each microsite occupied 1 in^2 (10 cm^2), this would be only 0.005% of the total area. Of course, this presumes that one germinable seed lands on each spot and is overlooked by mice and birds. It is worth noting that the ultimate outcome would also depend on what other vegetation might possibly appear on the other 99.995% of the area. Ordinarily the early mortality of seedlings is so large and the distribution so uneven that it takes more seedlings to achieve satisfactory natural regeneration. On the other hand, it is possible to have conditions so favorable that many seedlings survive on an acre (hectare) and grow into badly stagnated thicket stands.

Figure 5.3 A newly germinated pine seedling with the seed still encasing the cotyledons. *Source:* US Forest Service.

The crucial environmental characteristics of seedling microsites in relation to disturbance are very different from those that will govern the development of the tree after its top and roots have extended a few centimeters above and below the soil–air interface. The most important physical environmental factors to consider are: (1) degree of shade and leaf photosynthetic efficiency; (2) the variations in diurnal temperature; (3) soil water availability and plant water-use efficiency; and (4) soil nutrition and seedling nutrient-use efficiency (Table. 5.1). These factors are described in that order as a reflection of how a young germinant must cope with each factor at very different scales of temporal and spatial variability, beginning with the immediate and short time scales in which plants have to respond, and ending with time scales that are a reflection of years to thousands of years. For example, seedlings must respond to variabilities in light over the time periods of seconds (sunflecks) to hours (diurnal). Temperature regimes lag behind fluctuations in solar radiation but reflect similar degrees of temporal variability. Soil moisture availability increases and decreases over days and months in response to weekly and seasonal patterns in precipitation, and soil nutrient availability is dependent upon weathering processes that work on time scales of years to millions of years. Each of these factors is critical to germinant survival, but the physiological and morphological adaptations that a seedling possesses to cope with each limiting factor are hugely different in time and space.

Light

Light energy, photosynthesis, and their effects on seedling establishment and survival deserve particular attention. Solar radiation that comprises the visible parts (0.4–0.7 μm) and the infrared (0.7–10.0 μm) plays an important role in seedling survival. Light regimes beneath forest canopies can be dramatically altered by changes in the quality, intensity, and proportion of direct versus diffuse light (Nicotra, Chazdon, and Iriarte, 1999). Amounts and quality of light in forest understories can vary dramatically by forest type and season. For example, total daily light radiation received at the groundstory beneath a closed canopy of a late-successional evergreen tropical rainforest is normally less than 0.5% of that in the full open condition (Canham *et al.*, 1990; Ashton, 1992b; Ediriweera, Singhakmara, and Ashton, 2008). The majority of this radiation in evergreen rainforest (60–80% of the amount received) can occur over a 10-minute period of a sun fleck (Chazdon *et al.*, 1996). This means that if seedlings are to survive in such shady conditions they

Table 5.1 The temporal and spatial processes of light, soil moisture, and soil nutrition, and examples of mechanisms that plants have used to capture resource availability.

Temporal processes of light	**Adaptation response**
Hourly variation (canopy openings, sunflecks)	Immediate response to increased photosynthesis in leaves such that 10–20 minutes can provide 90% of the photosynthate
Diurnal variation (morning, midday, afternoon)	Highest rates of photosynthesis are usually mid-morning when sunlight is high but the day is still cool and moist
Seasonal variation (spring, summer, fall, winter)	Deciduous leaves allow trees to escape cold and drought. Young leaves peak in photosynthesis in spring. Peak activity is in the late spring or early summer in the wet season
Successional variation (stand dynamics)	Highest rates of photosynthesis during early-successional stand development
Intergenerational (generations of stands)	Genetic adaptation to changing climate
Temporal processes of soil water	**Adaptation response**
Hourly variation	Leaves close stomata, reduce water loss with increased temperatures of direct sunlight
Diurnal variation	Peaking temperatures in afternoon promote stomata closure
Seasonal variation	Deciduous leaves reduce water stress in the dry season and in onset of winter
Successional variation	Early-successional vegetation, less water-use efficient than late-successional vegetation
Intergenerational	Genetic adaptations to seasonal changes in soil water availability, drought and flooding. Symbiotic relationships with fungi
Temporal processes of soil nutrients	**Adaptation response**
Hourly variation	None
Diurnal variation	None
Seasonal variation	Lowered growth, photosynthesis, usually the most mobile and limiting nutrient is nitrogen
Successional variation	Changes in species composition from nutrient opportunists to nutrient conservers
Intergenerational	Genetic adaptations to nutrient use efficiency and nutrient acquisition. Symbiotic relationships with fungi

Source: Mark S. Ashton.

must be able to respond almost immediately to short bursts of sunlight to photosynthesize and assimilate stored carbohydrate for growth and survival (Chazdon and Pearcy, 1986, 1991; Chazdon *et al.*, 1996). Studies have reported amounts of light radiation beneath closed canopies to vary between 1 and 5% for mature temperate and boreal forests (Canham *et al.*, 1990; Fladeland, Ashton and Lee, 2003). Studies have also shown that the compensation point of seedlings (e.g., the balance between carbohydrate assimilated in photosynthesis and carbohydrate used in respiration) is closely correlated with the shade tolerance and successional status of the canopy (Canham *et al.*, 1994; Chazdon *et al.*, 1996). Lower compensation points are associated with seedlings of more shade-tolerant, later successional canopy tree species.

Stem exclusion in both natural forests and plantations are the most light-limiting periods of development in the understory for any plant. Plantations of deep-crowned conifers, such as Sitka spruce in the stem exclusion stage, can receive levels of daily light radiation that are as low as 0.1% (Fig. 5.4) (Lieffers *et al.*, 1999; Hale, 2003). During this phase of development, the understory has little or no regeneration or even understory herbs (Lieffers *et al.*, 1999).

Moisture and temperature affect the times when deciduous forest canopies have leaves that reduce solar radiation at the forest floor. Seedlings of many species thrive by being out of synchrony with canopy phenology. Some take advantage of this by early emergence and rapid photosynthesis before canopy leaf out in the early spring or onset of the rains. Others continue by delaying leaf

(a) (b)

Figure 5.4 **(a)** The dark shade within a young stem exclusion stage of an old-field white pine stand in New England, US. Note the near complete absence of an understory. **(b)** The deep shade of a stem exclusion stage mixed dipterocarp forest with a stratified canopy of pioneers on top (*Macaranga peltata*) and late-successional dipterocarps beneath (*Shorea* spp.) in a logged forest, Sri Lanka. *Source:* **(a, b)** Mark S. Ashton.

shedding in the fall or at the beginning of the dry season. In any event, amounts of light radiation in the understory of a closed canopy of a seasonally deciduous forest are considerably higher than in evergreen forests. Studies have shown light levels at the ground level of a deciduous forest to be 1–5% of the full open when canopy leaves are present, but 50–80% when the canopy is leafless (Lee, 1989; Canham *et al*., 1990; Chazdon *et al*., 1996).

The greatest differences in light radiation (both quality and amount) beneath a forest occur across canopy openings. Many plants grow very well in side shade where slanting direct rays of the sun are blocked by crowns of adjacent trees in the forest or opening edge. This condition is sometimes called "blue shade" because the light that is received is rich in the blue wavelengths of scattered diffuse light from the blue sky. "Green shade" exists where much of the light must come through several canopy layers of leaves in full shade. Because green light is photosynthetically useless to most plants, light that is rich in green only supports the most shade-tolerant of species. This kind of light can be observed on a sunny day beneath a mature beech or sugar maple forest. The light in the understory is noticeably a rich yellow. Both beech and sugar maple have such deep and shade-tolerant canopies that their understories are often barren of ground vegetation, since the light that reaches the forest floor is low in quality and impoverished of all but the greens and yellows of the light spectrum. The ratio of red to far-red solar radiation at ground level is used to define light quality. It can vary from 0.27 beneath a fully closed canopy, to 0.97 at the center position of a 2100 ft^2 (200 m^2) canopy opening, to 1.27 in the full open (Chazdon and Fetcher, 1984; Lee, 1987; Messier, Parent, and Bergeron, 1998; Lieffers *et al*., 1999). This ratio signifies the amount of photosynthetically useful red light that is received at the ground level compared to the amount of photosynthetically useless far-red radiation. The lower the ratio, the lower the amount of light is in photosynthetically useful red radiation.

Apart from changes in tree phenology and spatial heterogeneity of canopy structure, other factors that affect groundstory radiation regimes are related to physiography (slope, aspect) and latitudinal position and the actual structure of the forest canopy (Gray and Spies, 1996, 1997; Nicotra, Chazdon, and Iriarte, 1999). Under these circumstances, latitudes outside the tropics are strongly influenced by the angle of solar radiation during the growing season. Effects of aspect and slope are obviously of greater

significance at higher latitudes than at more equatorial latitudes (Canham, 1988). And obviously, as the height of the forest canopy declines with decrease in site quality, the amount of light radiation will increase for a given size of canopy opening (Ediriweera, Singhakumara, and Ashton, 2008).

Surface Temperature and Energy Transfers

In the first few inches (centimeters) of air above the forest floor, frictional effects greatly impede the turbulent transfer by which most vertical movement of heated air, water vapor, carbon dioxide, and other airborne substances takes place (Geiger, Aron, and Todhunter, 1995). The sluggish movement of air at the surface greatly restricts its upward transport of heat by day and correspondingly its downward movement to offset radiational cooling at night.

In this connection, it should be noted that much of the energy from the sun comes in the form of shortwave radiation that includes light (the visible portion of the shortwave spectrum). This energy comes through the atmosphere almost directly. The ozone of the ionosphere does absorb most of the life-threatening shortwave ultraviolet radiation. Otherwise, clouds, water vapor, and leaves are the only significant things that can shield the soil surface from solar radiation. The atmosphere is heated from below by heated land and water surfaces that re-radiate energy as longwave radiation, just as air is heated when it passes over a hot stove (Fig. 5.5). However, for plants, the temperature of their tissues is much more critical than that of the air around them.

The survival of new unshaded seedlings depends heavily on the interaction of the various physical processes by which this stupendous load of solar energy is dissipated (Ritter, Dalsgaard, and Einhorn, 2005). If heat accumulates, the surface temperatures soar; if it is lost too fast by night, the seedlings may freeze (Balisky and Burton, 1995). The processes that take heat energy away from the absorbing surfaces are reflection, convection, conduction, evaporation, and outgoing re-radiation. Although the important concern is usually the prevention of extremes of temperature, it is sometimes necessary to provide for temperatures high enough for germination.

Shading is the reflection or absorption of solar energy by leaves or other objects; it is the most important physical process subject to silvicultural manipulation (Asbjornsen *et al.*, 2004). Opaque objects obviously divert the radiation, but leaves have more complex effects of reflecting, absorbing, and transmitting radiation. The chlorophyll of leaves not only absorbs visible blue and red–orange light used in photosynthesis, but also reflects substantial amounts of green and, more importantly, invisible infrared light (Smith, 1982). A high proportion of the solar heating effect comes from longwave infrared radiation.

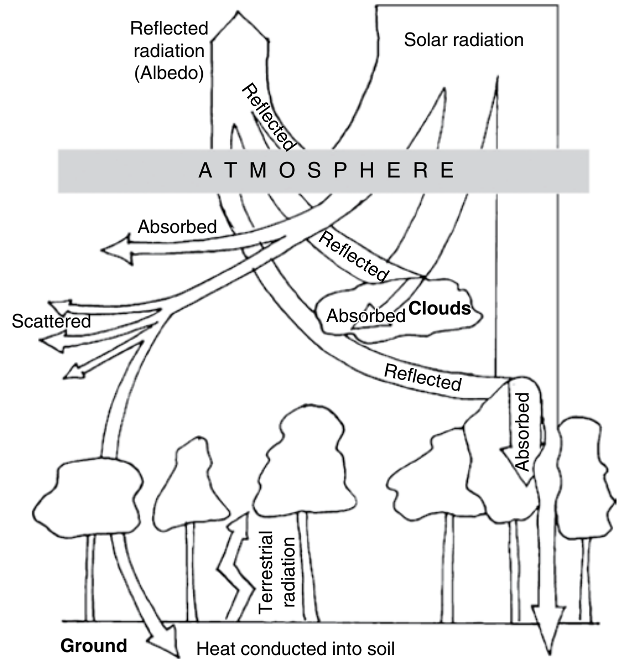

Figure 5.5 A depiction of the diurnal solar energy cycle between the earth's surface and the atmosphere. *Source:* Adapted from Geiger *et al.*, 1995.

Large amounts of radiation are reflected without ever being absorbed by the surface materials themselves. Most soil and dead organic materials do not vary much in their reflectivity or albedo. Therefore, not much can be done to foster seedlings by trying to modify surface reflectivity. Charcoal from forest fires, in spite of its blackness, is only slightly less reflective than unburned organic matter or exposed mineral soil almost without regard for their color. The wetting of surface materials slightly reduces their reflectivity. However, roughening the soil and litter surface to increase micro-heterogeneity can reduce heat loads, increase micro-shade, and decrease surface soil moisture evaporation, just enough to encourage germination and seedling establishment.

For practical purposes, the only way reflectivity can be used to control forest regeneration is to take advantage of the reflectivity of chlorophyll and the absolutely opaque rocks and wood. This does not always have to be by shade. Moss and other green vegetation growing around new seedlings can cool them by adding to the reflectivity of the green seedling leaves themselves.

The most important way by which heat moves vertically through air is turbulent transfer, which, with respect to heat, is called convection. This process involves the chaotic movement of large clumps of air molecules driven by the downward transfer of wind energy from the atmosphere hundreds of feet (meters) above. Conduction, the movement of heat through the collision of single molecules, transfers heat through the air very

slowly because there are so few molecules to collide. In fact, if the movement of heat upward from the surface depended only on air conduction, the temperature about 15 ft (5 m) above would be warmest in midwinter, and the midsummer surface temperatures would approach the boiling point of water.

The low heat conductivity of air is the cause of a phenomenon that can make the stratum immediately above the surface as dangerous for seedling tops as that for the roots below. The air in the first few fractions of inches (millimeters) is so tightly held by friction that convection has scant effect on it. The air molecules right next to solid materials can only vibrate and thus conduct heat; they cannot swirl and join in convection. Although this effect diminishes very rapidly with height, it makes the first few inches (centimeters) a bottleneck for heat transfer. If the surface temperatures rise above 122 °F (50 °C), as they readily can on some kinds of surface, the succulent stems of small seedlings can be girdled by heat injury.

Aside from providing shade, the best way to forestall severe surface heating is to stimulate downward conduction of heat by the soil. The denser the surface material, the more that heat will be conducted, and therefore the less extreme the surface temperature. Leaf litter, with its very large amount of included air, is nearly as low in conductivity as any naturally occurring substance. Some of the highest temperatures naturally induced by the sun on the face of the earth may be those of flat litter surfaces composed of small conifer needles like hemlock; these can reach as high as 170 °F (75 °C) (Gray and Spies, 1996). It is because of this and several other factors that the burning, physical displacement, or other modification of the unincorporated organic matter plays such a critical but manageable role in regeneration (Balisky and Burton, 1995; Gray and Spies, 1996).

The part of the organic matter that has finely divided humus does have good heat conductivity. Except for coarse sands, most bare mineral soil surfaces conduct enough heat downward to prevent fatally high surface temperatures. The heat conductivity of soil actually depends mostly on the relative amounts of air and water in it. Water is a comparatively good conductor, so the more water and the less air, the greater the conductivity.

Water has other important effects in stabilizing the microclimatic extremes of surfaces. Because of its remarkably high specific heat, it can absorb tremendous quantities of heat and yet its own temperature increases slowly. Its latent heat of evaporation is so great that large quantities of heat are absorbed, without change of temperature, when it changes from the liquid to the vapor phase. If the water vapor is then swept aloft, it carries large amounts of heat energy with it. Moreover, the latent heat of condensation is so low that large amounts of heat must be removed to convert it from a liquid at the freezing point to ice at the same temperature. In other words, the benefits of the properties of water to plants can be physical as well as physiological. However, the soaking of surface litter by rain postpones the extreme heating of such material by only about a half-hour once the direct rays of the noonday sun hit it.

The remaining heat-transfer process important for plant life is radiation. This occurs continuously and would do so even if there were no air. Much of the heat absorbed by the earth's surface materials is lost to outer space as infrared radiation of wavelengths even longer than those generated by the sun. The warmer the material, the more it radiates (see Fig. 5.5).

The same surface materials that absorb most of the solar shortwave radiation by day also lose most of this heat by longwave radiation at night and thus can become much colder than the air a short distance above. This creates risk of frost damage to plants, especially succulent seedlings. The sluggish movement of air in the boundary layer aggravates the problem even more than with heat injury during the day. During daytime heating, the heated clumps of air wrested from the surface layer are less dense than the cooler air around them and so they are convected aloft rapidly. At night, any warmer air that is pushed downward to replace very cold air at the surface must penetrate a denser medium. If the air is humid enough to leave a dew point higher than 0 °C, the condensation of water vapor into dew usually slows the cooling of plant tissues enough to prevent frost damage.

The most practical silvicultural method for preventing excessive radiational cooling is retention of overhead cover (Asbjornsen *et al.*, 2004; Ritter, Dalsgaard, and Einhorn, 2005). If the quanta of heat energy that radiates from a surface hits something above, rather than radiating fully to outer space, there is a strong statistical probability that some of the energy will bounce back to the original radiating surface and reheat it. There is a subtle difference between this kind of protective effect and that of daytime shading from direct solar radiation. The sun's rays come in directly at slanting angles (Fig. 5.6a), except at noontime in the tropics. The most effective route by which outgoing radiation can escape is straight up toward the zenith. This means that the side shade that helps in daytime may not help as much at night. In general, the wider the angle of the inverted cone through which radiation can escape unimpeded from any point, the greater will be the radiational cooling of that point.

Water Loss

Within the uppermost layers of the soil and organic material, water is lost to the atmosphere by direct evaporation. Such loss can proceed swiftly if the surfaces are exposed to direct solar radiation. The loose materials of

forest floor litter generally lose water so fast that they are seldom hospitable to the roots of plants. The uppermost layers of mineral soil or finely divided organic matter are somewhat more favorable but are also subject to water loss by direct evaporation. This comes about from the effects of surface tension in the very slender water columns within these materials. As water is lost to evaporation from the top ends of these columns, more is pulled upward to be lost in its turn. The finer the materials, the deeper is this capillary fringe. This kind of water movement differs from the transpiration of water by plants, which take up water from the soil through the roots. The important point about direct evaporation is that it explains the loss of water from the uppermost levels of the soil even when these layers contain no roots.

Fortunately, the strata from which water can be lost by direct evaporation are seldom more than several inches (centimeters) thick in total. If the roots of a new seedling do not quickly penetrate below this layer or are not repeatedly rescued by rain, the plant dies (Kozlowski, 1949). Shade and mulching effects can greatly slow down the direct evaporational losses but cannot add any new water. What this means then is that canopy shade of understory environments promotes surface soil moisture and mutes direct evaporation. However, at depths where roots are concentrated, usually just below the surface to 1 ft (30 cm), soil water is directly taken up through transpiration and thus seedling roots are in direct competition with a parent overstory. Such conditions below the surface can be very water limiting to regeneration, particularly during droughts, because the seedling roots are so much more ephemeral and restricted in area as compared to a tree's root system. However, the microsite location with greatest soil water stress is where there is the combination of direct solar radiation and tree root competition for water uptake. In northern latitudes, this would be on the northern edges of canopy openings (Fig. 5.6a,b) (Gray and Spies, 1997; Denslow, Ellison, and Sanford, 1998). There is a general trend in soil water availability at depths across openings that increases from understories into newly created gap centers because of lower direct uptake from competing vegetation (Gray, Spies, and Easter, 2002). However, the trend can be very variable because of microsite heterogeneity of old windthrows, and because of soil texture (Gray, Spies, and Easter, 2002). Soils with consistently

(a)

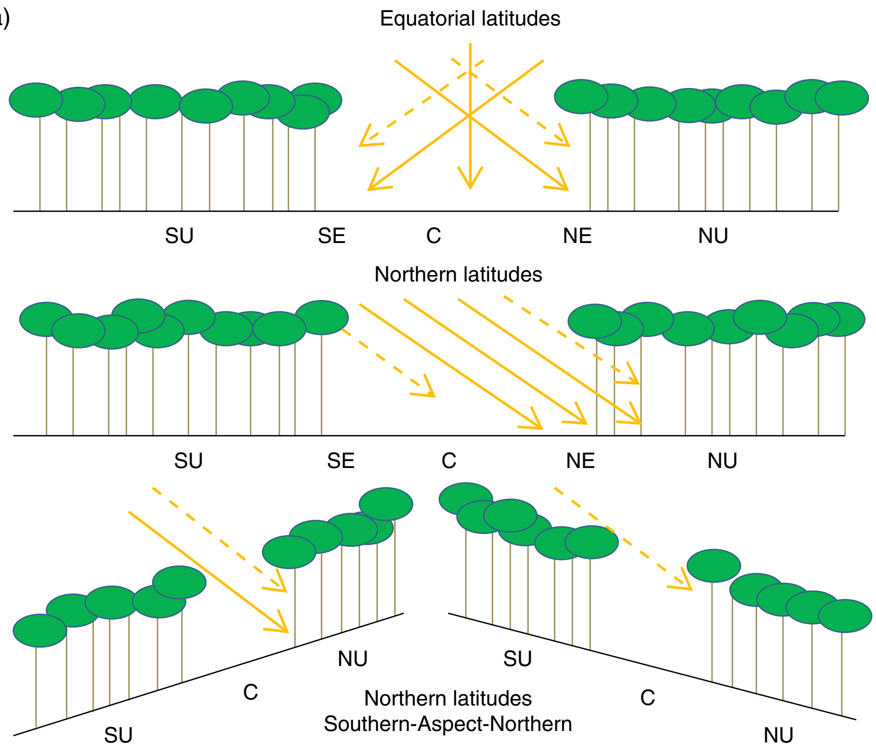

Figure 5.6 (a) A conceptual diagram depicting pattern of direct solar radiation across a canopy in the equatorial latitudes (top illustration) where the sun passes overhead twice (spring and fall equinox) over the year such that total solar radiation across an opening is concentric with highest amounts in the center (the amounts actually available to regeneration will depend upon when the rains are for growing season); over an opening in the northern latitudes (middle illustration) above the tropic of cancer (23 degrees north) (which would be the exact opposite should it be in the southern latitudes); over northern latitude openings (bottom illustration) where much more radiation is received on southern aspects. SU, southern understory; SE, southern edge; C, center; NE, northern edge; NU, northern understory.

(Continued)

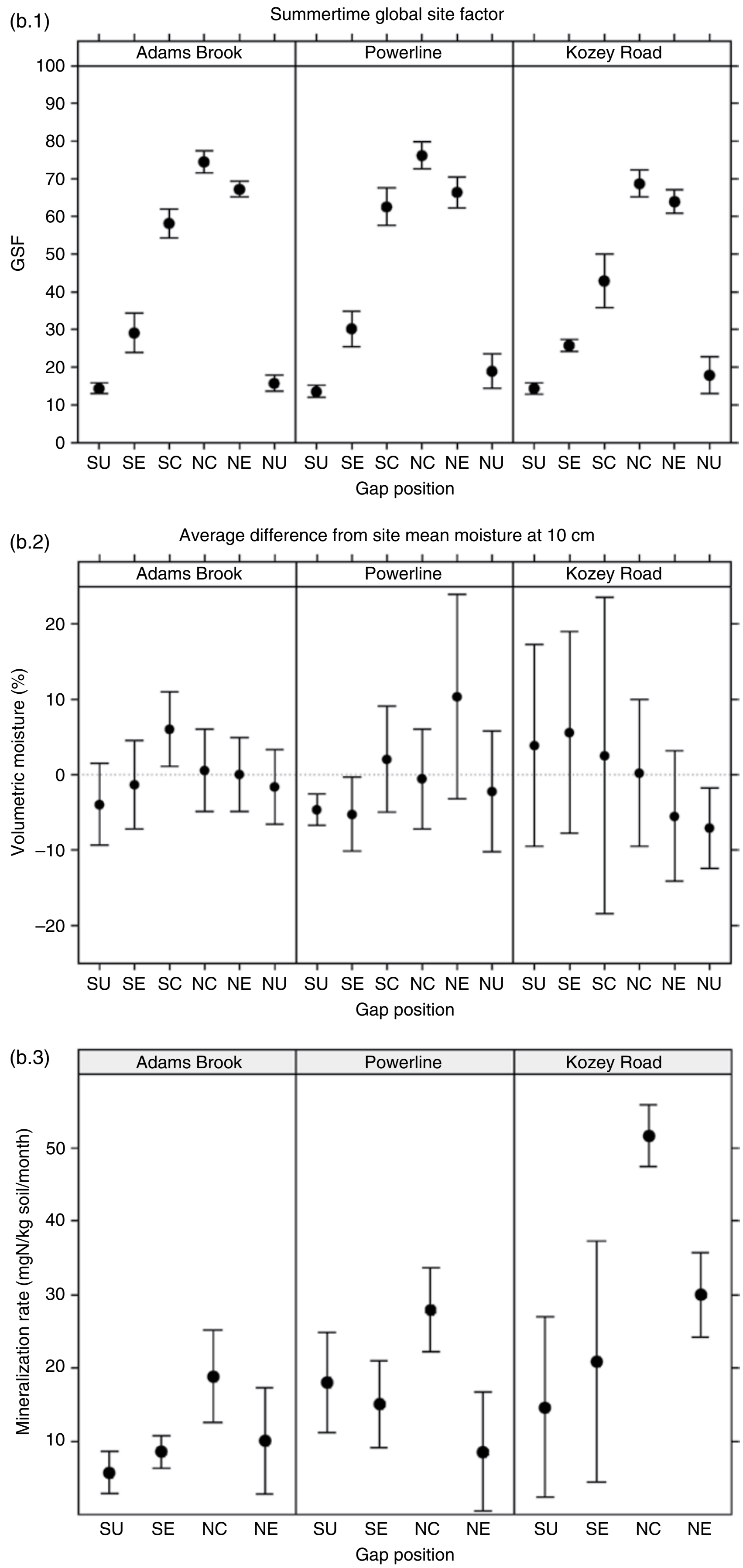

Figure 5.6 (Continued) **(b.1)** Means and variations of solar radiation (as measured by Global Site Factor, GSF), **(b.2)** soil moisture availability, and **(b.3)** soil nitrogen availability across three canopy openings, 1 year after creation on a sandy well-textured soil (Adams Brook), a thin to bedrock glacial till (Powerline), and a deep, fertile glacial till (Kozey Rd) in southern New England. Measurements were made over one growing season (June 1–September 1). SU, southern understory; SE, southern edge; SC, southern center; NC, southern center; NE, northern edge; NU, northern understory. *Source:* **(a, b)** Mark S. Ashton.

even and uniform texture (e.g., sands, loess, clay) create the most uniformly pronounced increasing and decreasing trends across the opening of a gap (Ashton *et al*., unpublished). Soils that are very irregular in texture with rocks and boulders (e.g., glacial tills) create considerable variability in microsite and soil water availability, and thus the trends are less noticeable (see Fig. 5.6b) (Ashton *et al*., unpublished).

Soil Weathering and Nutrient Availability

The fertility of soils is defined by degree of weathering (time), the geology, and the climate. Geology can be defined by *in situ* weathering where soils are derived directly from the underlying bedrock or by materials that have been moved and then weathered to form soil. Here the geology underneath is often unrelated to the geology of the material which has been moved on top. Ongoing material moving processes can be categorized as alluvial, colluvial, or wind deposition. Material that was moved in the past can be categorized as glacial activity or volcanism. The degree of weathering to form soils and to make nutrients available from the rock materials is obviously dependent upon time, but more importantly, it is dependent upon the erodibility of the rock itself and the nature of the climate. Warm moist climates, with high precipitation and seasonal periods of dryness and heat, break rocks down much faster than consistently dry or consistently cold environments. The kind of geology also determines erodibility, with soft sedimentary rocks, like limestones and shale, being more erodible than igneous and hard granite. Finally, the fertility of the soil is dependent upon the actual mineral content of the rocks. Granites and sandstones, which are comprised mostly of quartz, are noticeably poorer in nutrients, and create coarse-textured, acidic, drought-prone sandy soils. Igneous rock, such as basalt, provides for more finely textured mineral-rich soils. Given the fact that all these factors contribute to soil fertility, it is the length of time that is the most important variable which has allowed plants to evolve and adapt to differences in soil. The nature of soil and plant adaptation to site is one that has evolved over thousands and even millions of years. Plants adapted to particular kinds of soils and sites have been defined in the literature as site restricted or site specialists (Bormann and Likens, 1979; Huston, 1979; Clark, Palmer and Clark, 1999; Wright, 2002). Plants with wide ranges irrespective of soil can be considered site generalists (Bormann and Likens, 1979; Wright, 2002).

Generally the most weathered soils are *in situ* and occur in tropical environments. Such soils are the most limiting in minerals and nutrients because over millions of years the nutrients have been leached and lost. Many late successional species, particularly in tropical forests, have been shown to be site restricted, where different species, even within a single genus, have specific distributions related to soil nutrition (Fig. 5.7). In such circumstances, certain species and families of trees have developed mechanisms for nutrient-use efficiency. For example, the oaks, pines, and rhododendrons are within families of plants (Fagaceae, Pinacaeae, Ericaceae) that are often associated with acidic, droughty, or low-fertility soils derived from rocks such as granites and sandstones. Such families have been shown to have symbiotic relationships between their roots and ectomycorrhizae fungi, where the fungi serve to greatly increase root area and improve uptake abilities of soil water, phosphorus, and magnesium in exchange for the plant providing the fungi a source of sugar. On extremely weathered and old landscapes of southeast Asia and Central Africa, the tree families Dipterocarpacaeae and Caesalpinoideae (Leguminosae subfamily) respectively form monodominant stands within the forest using such mycorrhizal fungi (Hall *et al*., 2004; Palmiotto *et al*., 2004).

Of all the weatherable nutrients from rocks, calcium is likely the most easily leached, particularly on forest soils that are predominantly acidic. In eastern North America, it is the nutrient most susceptible to loss from harvesting, acid rain, and general leaching processes compared to phosphorus, magnesium, and potassium (DeHayes *et al*., 1999; Lovett and Mitchell, 2004). Calcareous soils derived from limestone or marble are more basic, with higher levels of cation exchange and fertility. Such soils define species and floristic associations that are highly productive but site restricted, such as basswood, sugar maple, and the herbaceous indicator plants represented beneath.

Finally, nitrogen is easily the most mobile of the major nutrients that seedlings and plants require. It is also the one nutrient that is incorporated into the soil largely from atmospheric and biological processes as opposed to weathering (Boerner and Koslowsky, 1989). Interestingly, nitrogen can be the most limiting nutrient to trees and forests where soils and weathering processes are young and where weatherable nutrients are more available but the nitrogen has been lost to the atmosphere (Vitousek and Howarth, 1991). Examples of young soils are represented by landslides and floodplains, which are often associated with active tectonic topography and mountains and from disturbance such as fires (Guenther *et al*., 2000; Perakis and Hedin, 2001). In these circumstances, nitrogen is easily volatilized and lost, making it the most limiting for vegetation recovery (see Fig. 5.6b). Nitrogen can be added rapidly back into the soil through fast-growing pioneers that can fix nitrogen (Vitousek and Howarth, 1991; Galloway *et al*., 2004). Plants that fix nitrogen are primarily in the the pea and mimosa subfamilies of the Leguminosae and alders. In many forest regions such as eastern North America, nitrogen is now not so limiting because of air pollution due to the burning of fossil fuels (Aber *et al*., 1998; Galloway *et al*., 2004).

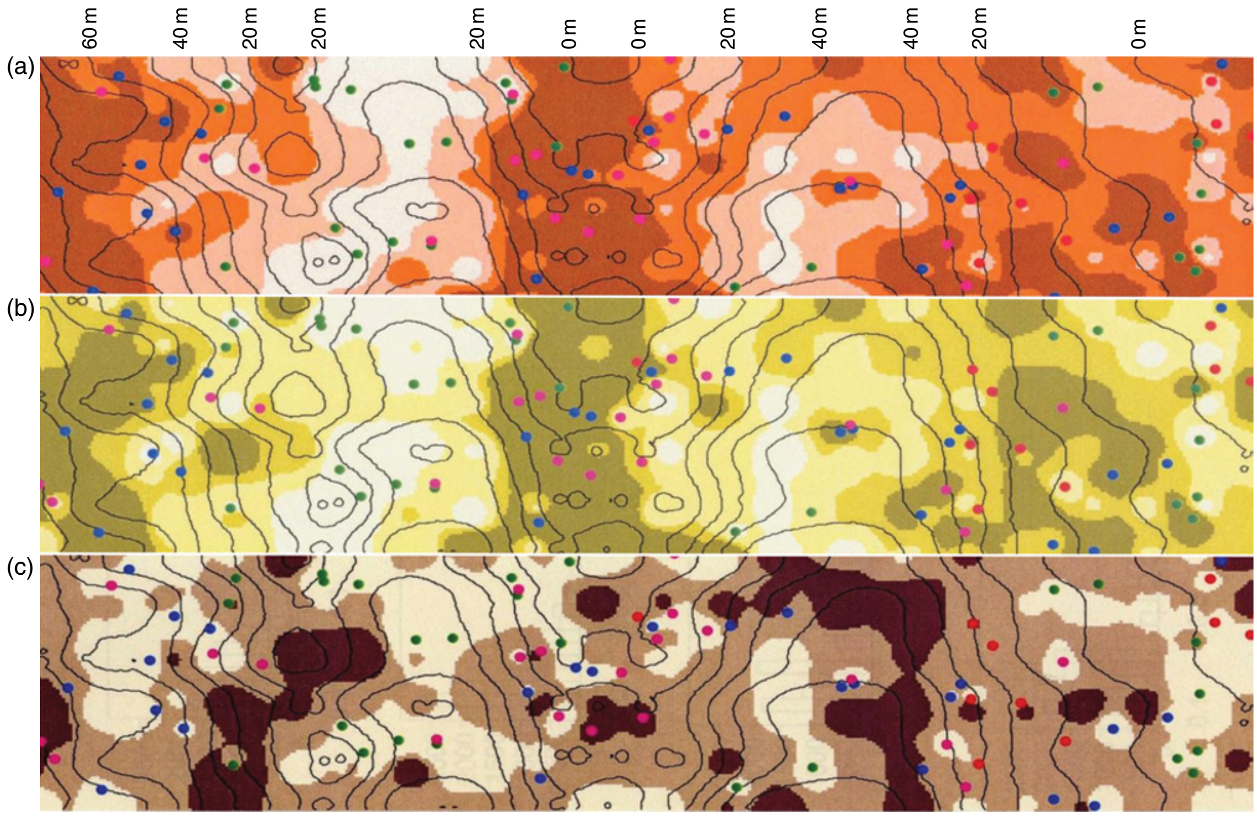

Figure 5.7 The distribution of four species of *Entandrophragma* (African mahogany). Individual trees are depicted by the pink, blue, and green circles, in relation to soil nutrient availability [**(a)** calcium – oranges; **(b)** magnesium – yellows; **(c)** phosphorus – browns] on an old sedimentary oxisol in a Central African rainforest. *Source:* Adapted from Hall *et al*., 2004.

The Regeneration Process

The chief purpose of the preceding account of surface and subsurface microclimate is to show how the success of seedling regeneration and the kind of species that establish can be regulated to some extent by deliberate manipulation of overhead cover and the characteristics of the surface materials.

However, successful natural reproduction depends on the completion of a long sequence of events (Wenger and Trousdell, 1957; Grubb, 1977). Failure of any single link in the chain can be fatal. As far as sources of regeneration are concerned, there is the basic difference between sexual regeneration from seed and asexual regeneration from various modes of vegetative sprouting. All tree species can regenerate from seed, but some are so dependent on vegetative sprouting that the capacity of sexual reproduction seems to be retained only as a nearly vestigial capacity for further evolutionary adaptation.

With natural reproduction, species can be assembled into autecological groups. These categorizations have been based on the nature of the regenerative mechanism and stage of regeneration event (i.e., flowering, seed supply, seed dispersal, storage, germination, succulent stage, growth, and establishment). For example, during seed dispersal, differences can be observed in the dispersal mechanism between (1) new seed carried in from outside the stand being regenerated, (2) seeds "stored" on site on the trees (as in unopened serotinous cones), or (3) those in the forest floor as ungerminated seeds. Finally, various kinds of advance growth include another kind of regeneration that may be "stored" on site as (4) seedlings or seedling sprouts, or as (5) vegetative sprouts that can arise from (a) basal portions of stems ("stump sprouts") (Fig. 5.8), (b) root systems ("root suckers"), or (c) rooted branch ends ("layers"). For further description of vegetative reproduction, see Chapter 12. Artificial regeneration can result from the sowing of seeds on the site or from the planting of seedlings or vegetative cuttings started in the nursery or greenhouse.

Plants can be dispersed and established in a large number of ways. If a detailed classification of the sets of ecological adaptations of species was set up, it would soon be apparent that each species of a given locality seems to have its own separate pigeon hole. Similar sets of adaptations for ecologically similar groups of species,

Figure 5.8 Not all forests grow on dry land, nor do all regenerate only from seeds. It may be anticipated that a good tree will develop from one of these 2-year-old stump sprouts of water tupelo in a very wet part of a flood-plain or bottomland forest in Mississippi. *Source:* US Forest Service.

which are often referred to as **guilds**, can usually be found among representatives from geographically separated regional flora. However, one species seldom exhibits exactly the same adaptations throughout its natural range. The only real solution to the problem is to find out as much as possible about the regeneration requirements of each species in each locality. For purposes of simplification only five broad guilds of propagule regeneration will be used (Table 5.2).

Mechanisms of Essential Stages of Natural Regeneration

Flowering

Almost all tree species have the capacity to sexually reproduce through a variety of breeding systems (Table 5.3). The nature of the sex of a flower is an important component of differentiating breeding systems among species and in classifying their plant families (Bawa and Hadley, 1990; van Schaik, Terborgh, and Wright, 1993). Species that are monoecious have functional sexes on the same plant but in separate flowers. Dioecious species have trees with flowers of only one functional sex. Plant species that are perfect have both functioning sexes within the same flower.

Although species differ in how sexes are florally represented, all have adopted various strategies to create a viable propagule that will contribute toward maintaining and advancing the genetic vigor of the future population. To the forester, this can provide a dilemma that requires a careful balance between maintaining the viability of a population and selecting individuals with certain genetically desirable traits of economic importance (National Research Council, 1991). Unlike annual agricultural crops, trees must endure environmental variability over a much longer period of time with considerably slower intergenerational responses to environmental change.

To maintain genetic vigor, pollination that crosses one parent tree with another is the most desirable. This is called outcrossing and almost all tree species promote outcrossing to maximize genetic mixing among a population. Many temperate canopy trees that are wind pollinated, such as the pines and oaks, are moneocious whereby flowers are of separate sex but borne on the same tree. To promote cross-pollination, sexes are displayed on different parts of the crown, or mature at different times to avoid self-pollination.

Many canopy trees of the tropics have perfect flowers. Because canopy trees of the same species in a tropical forest can be widely dispersed, many researchers previously believed that these species were largely self-pollinated. Studies have revealed that specific animal pollination vectors ensure much higher outcrossing than originally imagined (Hamrick *et al.*, 1991). Although most forests do not have a major proportion of dioecious tree species, both Bawa (1980) and Givnish (1980) have reported that the trait increases when moving toward forests of more equatorial latitudes. This can largely be related to the closer co-evolutionary and predictable relationships that have developed between plants and animals in these climates (van Schaik, Terborgh, and Wright, 1993).

Many tree species in more unfavorable environments have resorted to maintaining genetic vigor through **vegetative propagation**. Although no further advances in genetic adaptation to environmental change are likely via this route, the ability to hold onto a site without needing to relinquish growing space is an enormous competitive advantage. Vegetative sprouting, layering, and suckering are most common in montane krumholtz, forest understories, and frequently disturbed sites.

A few species have evolved to solely promote self-pollination. This has favored the retention and passing of certain genetic traits from parent to offspring, particularly where these traits provide a competitive advantage

Table 5.2 Autecology of tree propagules of forests and woodlands.

Regeneration guild	Mode of dispersal	Life history traits	Disturbance type	Species examples
1) **Very small winged seed** dispersed into the stand from outside	Wind, small birds, mammals	Seed that is abundant and small; light-demanding pioneers that are usually short lived. Site generalist	Lethal severe – landslides, sediments from floods, exposed mineral soils	Birch, poplar, willow
2) **Medium winged seed** dispersed from nearby trees	Winged seed, aided by wind, but relatively large and poorly dispersed	Shade-intolerant long-lived canopy emergent. Long-lived pioneers but many can be site restricted	Lethal severe – crown fires and windstorms where legacy trees survive	Yellow-poplar, mahogany, Douglas-fir, western larch, hard pines
3) **Seed stored on the tree** or on the ground surface	Gravity, wind, and explosive dehiscence	Borne within protective woody cones or pods; small-seeded; light-demanding pioneers that can be long lived	Lethal severe – promotes release of seed – fire	Lodgepole, jack and pitch pines, some eucalypts
4) **Buried seed** stored in mineral soil	None – accumulating seed bank from small mammals and birds	Medium-sized seed, light-demanding pioneers. Site generalist	Lethal severe – promotes germination of seed from changes in soil environment	Pin cherry, black cherry, raspberries
5) **Vegetative propagation** that arises from stems, roots, and branches of residual parent plants. Most species in other than the regeneration guild can also propagate vegetatively, particularly before reproductive maturity	Original parent root systems	a) **Fast-growing early- to mid-successional tree species** that are stress adapted	Releasing severe – promotes death of aboveground parts of residual trees but allows survival of roots	**Canopy trees** – oak, maple, ash, alder, poplar, redwood, incense cedar
		b) **Shade-tolerant (enduring), slow-growing understory trees and shrubs**	Understory environments and small-scale release events promote continuous spread of understory trees and shrubs	**Understory shrubs and small trees** – viburnums, dogwoods, witch hazel, understory maples (vine and striped)
6) **Masting large-seeded nuts** advance growth, seedlings, seedling sprouts, and saplings that originate as cohorts during mast years	Hoarding mammals, hoarding birds, and gravity	Seed successfully germinates sporadically as a cohort. Seedlings accumulate beneath a closed forest canopy as a seedling bank carpeting the groundstory. Large-seeded mid- to late-successional species. Intermediate to very shade tolerant. Clumped distributions often **site restricted**	Releasing of variable degrees – promotes release of groundstory regeneration. Windthrows of all kinds, canopy herbivory, and pathogens	Oak, maple, spruce, fir, hickory, walnut, white pines, hemlock, dipterocarps
7) **Non-masting large-fruited seeds** effectively dispersed away from parent trees by animals. Advance- growth of seedlings, seedling sprouts, and saplings that originate almost continuously from year to year in small amounts	Bats, primates, and large birds. Seeds require ingestion by animal	Seed successfully germinates seasonally but regularly in small amounts beneath a closed forest canopy. Large-seeded, shade tolerant, and as a seedling susceptible to herbivory. Scattered distribution. **Site generalist**	Releasing – as above but mostly associated with tropical canopy tree species	Durians, persimmon, virola, mango, avocado

Source: Mark S. Ashton.

Table 5.3 Modes of pollination and related characteristics of flowers and fruits.

Agents	Active times	Colors	Odors	Flower shapes	Nectar	Examples
Insects as primary agents of pollination						
Beetles	Day and night	Usually dull	Fruity or aminoid	Flat or bowl-shaped; radial symmetry	Undistinguished if present	*Myristica* (nutmegs), *Annonia* (soursop), *Polyalthlia*
Carrion and dung flies	Day and night	Purple–brown or greenish	Decaying protein	Flat or deep; radial symmetry; often traps	If present, rich amino acids	*Sterculia*, *Theobroma* (cacao)
Hover, flower, and bee flies	Day and night	Variable	Variable	Moderately deep; usually radial symmetry	Hexose-rich	Orchids
Bees	Day and night or diurnal	Variable but not pure red	Usually sweet	Flat to broad tube; bilateral or radial symmetry; may be closed	Sucrose-rich for long-tongued bees, hexose-rich for short-tongued	Basswood, horse-chestnut, willows
Hawkmoths	Evenings or nocturnal	White, pale or green	Sweet	Deep, often with spur; usually radial symmetry	Ample and sucrose-rich	*Capsicum* (peppers), potato, tomato
Settling moths	Day and night or diurnal	Variable but not pure red	Sweet	Flat or moderately deep; bilateral or radial symmetry	Sucrose-rich	Dipterocarps, *Genetum*
Butterflies	Day and night or diurnal	Variable; pink very common	Sweet	Upright; radial symmetry; deep or with spur	Variable, often sucrose-rich	*Elaeocarpus*, *Hedyotis*, citrus, coffee
Vertebrates as primary agents of pollination						
Bats	Night	Drab, pale; often green	Musty	Flat "shaving brush" or deep tube; radial symmetry; much pollen; often upright, hanging outside foliage, or borne on branch or trunk	Ample, and sucrose-rich	*Durio* (durian), *Sonneratia* (mangrove), balsawood, kapok
Birds	Night	Vivid, often red	None	Tubular, sometimes curved; radial or bilateral symmetry; robust petals; often hanging	Ample, and sucrose-rich	Catalpa, *Erythrina*, *Spathodea* (African tuliptree)
Abiotic pollination						
Wind	Day or night	Drab, green	None	Small; sepals and petals absent or reduced; large stigmata; much pollen; often catkins	None or vestigial	Oaks, pines, beeches, firs, spruces
Water	Variable	Variable	None	Minute; sepals and petals absent or much reduced; entire male flower may be released	None	Podocarps

Source: Data derived in part from Howe and Westley (1988), Baker and Baker (1983), Proctor and Yeo (1972), Faegri and van der Pilj (1971), Baker and Hurd (1968).

over other species. Environments that promote this reproductive strategy are largely similar to those that promote vegetative modes of propagation, such as alpine meadows and highly disturbed sites. Although these plants carry the traits that promote their survival on these sites, they are genetically very similar due to continuous self-pollination. Under these circumstances, these species are much more prone to having propagules that have a lethal recessive **genotype**. Fortunately, such genotypes seldom enter the general population because lethal recessive genes usually cause the seeds to abort.

Seed Supply

The first and most obvious prerequisite for regeneration is an adequate supply of seed. No tree or group of trees is a dependable source for propagation unless it is sufficiently mature and vigorous to produce seed. Furthermore, seed bearers should be located so that wind or other agencies will properly distribute the seeds over the area to be regenerated. Regardless of how carefully the seed bearers are chosen and fostered, it must be remembered that many species do not annually produce the abundant crops of seed necessary for satisfactory regeneration (e.g., oaks, hickories, and beech; Chambers and MacMahon, 1994). This characteristic makes it difficult to carry out reproduction cuttings with equal chance of success each year. The limited crops of seed that are produced almost every year give rise to little or no reproduction. The origin of many stands can be traced to unusually good "seed years" that were followed by satisfactory conditions for germination and establishment of seedlings. This implies that silviculture needs to space and hold seed-bearing trees on site after harvest in many circumstances to secure adequate regeneration establishment of certain tree species in a new forest.

Good seed years occur at intervals that are better thought of as sporadic rather than predictably periodic (Sakai *et al.*, 1999; Kelly and Stork, 2002). Although there might be real cycles of seed (mast) production, they are complicated and have yet to be verified or explained. The first essential is an ill-defined state of physiological readiness for flowering; the supply of nitrogen compounds for protein building may be one of the crucial factors. Even after flowers or strobili appear, it is common for adverse weather or infestations of insects and fungi to intervene and prevent pollination or maturation of flowers and fruit. The depredations of insects are a common cause of irregularity for seed crops (Chambers and MacMahon, 1994; Clark *et al.*, 1999). Sometimes good seed crops follow years of total failure that may have caused the collapse of populations of specialized seed predators (see the later section on the predator saturation hypothesis) (Kelly and Stork, 2002). In general, the more favorable the conditions of soil and climate for plant growth, the more frequent are good crops of seed (Clark *et al.*, 1999).

Seed Dispersal

The modes of dissemination of tree species include almost every imaginable mechanism (Table 5.4). The distances of effective dispersal vary widely but for late-successional trees are usually not greater than a few times the height of the seed bearers (Clark *et al.*, 1999; Nathan and Muller-Landau, 2000). With many wind-disseminated species, particularly the conifers, seeding is not uniform in all directions because dispersal is effective when dry winds are blowing. With species disseminated by birds, bats, mammals, gravity, or flowing water, it is important that the forester proceed with clear understanding of the factors involved. Some adaptations are quite bizarre. For example, the seeds of some tropical mangrove species germinate on the trees, and the fallen seedlings can then float upright over miles of ocean to take root on some distant shoreline.

Both before and after the seeds fall from the trees, they are likely to be eaten by insects, bats, birds, and rodents. Although seed predators are held in check by natural controls that may be strengthened by direct or indirect artificial measures, the most practical means of overcoming predation is to ensure that the supply of seed is sufficient both to feed the predators and to regenerate the forest. For silviculture this means that all kinds of considerations need to be made about how to plan for and adequately disperse seeds through the retention and spacing of parent trees. Sometimes the most important predators are also the most effective agents of dissemination; if it were not for squirrels and other rodents, the heavy seeds of oak, hickory, and walnut would not be carried and buried or cached farther than gravity would take them. Edible fruits are often adaptations for seed dispersal by animals especially birds, primates, and tropical fruit-eating bats, whereby the pulp is the incentive and is eaten and the actual seed is passed through the gut or discarded. Such dispersal strategies are some of the most co-evolved between plant and animal and result in high success such that only a few large fruits need be produced (Clark *et al.*, 1999; Nathan and Muller-Landau, 2000) (Table 5.4).

Seed Storage

Seeds are usually produced during a favorable period but must often survive a dry or cold period and be ready to germinate during the next growing season. To do this, they develop varying degrees of dormancy, a condition in which they do not grow and their physiological processes become very slow. This dormancy can become sufficiently pronounced that the seeds will not germinate until particular conditions have been met. This phenomenon often

Table 5.4 Modes of dispersal and related characteristics of seeds or fruits.

Agents	Colors	Odors	Forms	Rewards	Examples
Usually self-dispersal					
Gravity	Various	None	Various	None	Oaks, hickories, dipterocarps
Explosive dehiscence	Various	None	Explosive capsules or pods	None	*Acacia*, *Croton*, dwarf mistletoe
Bristle contraction	Various	None	Hygroscopic bristles in varying humidity	None	Rubber
Usually abiotic dispersal					
Water	Various, usually green or brown	None	Hairs, slime, small size, or corky tissue resists sinking or imparts low specific gravity	None	Bald-cypress, sycamore
Wind	Various, usually green or brown	None	Minute size, wings, plumes, or balloons impart high surface to volume ratio	None	Birches, ashes, elms, maples, willow, cottonwood
Usually vertebrate dispersal					
Hoarding mammals	Brown	Weak or aromatic	Tough, thick-walled nuts; indehiscent	Seed itself	Oaks, hickories, walnuts, *Dipteryx*
Hoarding birds	Green or brown	None	Round wingless seeds or nuts	Seed itself	Pinyon pine, whitebark pine
Arboreal frugivorous mammals	Brown, green, white, orange, yellow	Aromatic	Often arillate seeds or drupes; often compound; often dehiscent	Aril or pulp rich in protein, sugar, or starch	*Mangifera* (mango), *Nephelium* (rambutan)
Bats	Green, white, or pale yellow	Aromatic or musty	Various, often pendant or starch	Pulp rich in fat	Banana, figs
Terrestrial frugivorous mammals	Often green or brown	None	Tough, indehiscent, often >50 mm long	Pulp rich in fat	Blueberry, *Parkia* (petai)
Highly frugivorous birds	Black, blue, red, green or purple	None	Large arillate seeds or drupes; often dehiscent; seeds >10 mm long	Pulp rich in fat or protein	*Virola*, *Myristica* (nutmegs), *Durio* (durians)
Any frugivorous birds	Black, blue, red, orange, or white	None	Small or medium-sized arillate seeds, berries or drupes; seeds <10 mm long	Various; often only sugar or starch	Cherries, raspberries
Animal fur or feathers	Various	None	Barbs, hooks, or sticky hairs	None	Grasses and sedges
Usually insect dispersal					
Ants	Various	None to humans	Oil-secreting seed coat	Oil or starch body with chemical attractant	*Banksia*, *Protea*, *Macaranga*

Source: Data derived in part from Howe and Westley (1988), Gautier-Hion *et al*. (1985), Janson (1983), Wheelwright and Orians (1982).

prevents seeds from germinating prematurely, as during abnormal warm periods of winter.

The required conditions are often those that prevail in the forest litter or soil during periods unfavorable for germination. For example, many species will not germinate without a period of moist storage at low temperature, known as **stratification**. Some bird-disseminated species have seeds with hard coats that must be abraded by the sand in bird gizzards before water and oxygen can penetrate the seed and start germination, known as **scarification**. Where seeds are stored artificially, it may be necessary to carry out treatments that imitate those that break dormancy in nature (e.g., chilling oak acorns for a period of time to stimulate germination).

The seeds of many species in aseasonal tropical rainforests do not develop dormancy because conditions are always favorable for growth and there is no value in delaying germination. They must germinate in hours or days and are difficult or impossible to store artificially. Such seeds are known as **recalcitrant**. At the other extreme, the seeds of some species can survive for many years under natural or artificial conditions in which respiration is kept very slow (but not halted) by dryness, low temperature, or limited aeration. For example, the forms of jack and lodgepole pine that are adapted to regenerate after forest fires have seeds that are stored for decades in sealed cones (known as **serotiny**) on the trees (Lamont *et al.*, 1991). When hot fires melt the cone scales, the seeds are released onto the bare soil left by fires (Burns and Honkala, 1990). The **buried seed** phenomenon is another example whereby certain plant species can store seeds in the forest soil for long periods of time (in some cases thousands of years, e.g., *Rubus*) and germinate only after a canopy disturbance alters the ground surface radiation and moisture regimes (Leck, Parker, and Simpson, 1989).

Germination

The start of development of the embryo depends on having adequate amounts of moisture, heat, oxygen, and sometimes certain wavelengths of red- to far-red light. However, successful germination depends largely on the rainfall and the nature of the spot where the seeds are deposited. Moisture is the most critical and variable factor. The embryos in excessively dry seeds either die or remain dormant. If the seedbed is too wet, the seeds will rot without germinating, or they will suffer from deficiency of oxygen (Bewley, 1997; Baskin and Baskin, 1998).

In general, the seeds of wind-disseminated species germinate best on or slightly beneath the surfaces of seedbeds that tend to remain moist. Bare mineral soil is usually the best seedbed for such species. Seedbeds of horizontally oriented materials, such as coniferous litter, tend to be unfavorable because they inhibit penetration of seeds into moist substrata (Baskin and Baskin, 1998). Vertically arranged leafy material, like grasses, are less resistant. Delays in germination are dangerous because they lengthen the period of exposure to birds and rodents. Losses from germination failure, which are usually caused initially by desiccation of seedbeds, are frequently more serious than losses of germinated seedlings.

Because of differences in species rooting ability to penetrate the ground surface, many of the microsite differences of surface soils and their alterations can be used to determine species suitability. Close examination reveals many differences among species, but most are poorly documented. Much of the difference in species establishment depends on how deeply fire or physical disturbance has exposed various soil layers. In general, the only species that can effectively establish themselves on thick leaf litter are those that have large seeds (Carvell, 1979; Baskin and Baskin, 1998). However, this is not because they can germinate on top of such surfaces but because they are buried beneath them by caching rodents and birds or more falling leaves and because they have enough stored materials to grow back up through the leaves. Oak acorns and other large seeds usually cannot successfully germinate on bare soil surfaces. Their new, blunt roots simply roll them around over the surface without penetrating. They need to be buried to be held in place and kept moist. If smaller-seeded species appear to have established themselves on thick litter, close examination usually shows that it was on some localized spot where wind or something such as a little ant mound made the litter very thin. Most small-seeded species can germinate only on dense media such as exposed mineral soil from windthrow mounds. This is mainly because close contact must exist between the seed and the moisture-supplying medium. Even then, the germination is seldom good unless the action of rain, frost, or other agencies has caused the seeds to be slightly buried.

With dense seedbed media, it can make a large difference how deeply they are exposed and what sort of materials form the surface. One of the most ideal seedbeds for some very small seeds, such as those of birches, is the finely divided black humus of the layer above the true mineral soil (Baskin and Baskin, 1998). This has the appropriate density coupled with high concentration of chemical nutrients suited for small-seeded species lacking seed resources. However, some species (subalpine fir, Englemann spruce) can have poor germination on their own unsterilized litter (Daniel and Schmidt, 1972).

The uppermost strata of mineral soil are favorable for many species with seeds of small or medium sizes. For reasons that are not altogether clear, the number of species that can become established seems to dwindle the more deeply the soil is gouged. Sometimes they become limited to sedges or plants other than trees. It is rare that

there is any useful purpose in extending seedbed preparation any deeper than the surface of the mineral soil except to bury the seeds slightly or to alter the drainage characteristics of the soil.

Succulent Stage

New seedlings are most vulnerable during the first few weeks of their existence, while their stems are still green and succulent. Heat injury resulting from extremely high temperatures on surfaces exposed to direct solar radiation takes a heavy toll, particularly among conifers. Tender seedlings in shaded situations are subject to **damping-off** caused by a wide variety of weakly parasitic fungi that are normally saprophytic and incapable of attacking larger seedlings (Baskin and Baskin, 1998). Cutworms and other insect larvae are particularly active during this period; most of the species involved are omnivorous feeders that will eat anything green and succulent. The better known forest insects and fungi generally attack trees that have passed the succulent stage. Seedlings that germinate late and remain succulent in the fall are commonly killed by frost. The dangerous succulent period ends when the cortical tissues of the stem become dry and straw colored, a process referred to as **hardening**. Thereafter the attrition of various damaging agencies continues, but catastrophic loss has ended.

Growth and Establishment

The physical environmental factors that control small, new seedlings may not operate the same after the roots have penetrated below the capillary fringe and the tops have grown up into the more turbulent air strata. Once the seedling is tall enough, and at all subsequent stages of development, it is not as threatened as much by extremes of temperature. However, the risk of frost damage persists longer than that of true heat injury. There is still the need for all kinds of adaptations to restrict excessive water loss, but there is usually enough turbulent convection to address other microclimatic problems.

A crucial race against time which the seedling makes is that of extending its roots downward faster than the loss of water through direct evaporation from the capillary fringe can overtake them. After this penetration is achieved, the roots move permanently into soil strata in which water loss is governed by gravity and transpiration, not by direct evaporation. Only the transpiration of established plants can move water upward from these strata. The less established vegetation there is to transpire, the better the supply of water beneath the first few inches (centimeters) will be. This is one reason why shaded seedlings are sometimes more likely to die of drought than those growing in the open.

Great variations exist in the growth rates and ways seedling roots penetrate downward to the relatively stable moisture supplies available at depth (Baskin and Baskin, 1998). Most species germinate at a certain time of year when the soil is well supplied with water. If the ensuing period is rainless, as in the western US, or subject to drought from high evapotranspiration, as in parts of the southern US, everything depends on whether the seedling roots can extend downward more rapidly than the drying front that moves downward from the surface. Most of the species in these regions are adapted to produce roots that grow 6–20 in (15–50 cm) deep the first year. If the necessary building material cannot be provided from the seeds, there must be enough light for adequate photosynthesis, or the seedlings simply die of drought in the shade, unable to build roots deep enough.

In regions where there is regular and abundant rainfall, seedlings are often adapted to survive with much shallower root systems. However, it is good to note that moistening of the soil from rain can proceed only to the extent that there is enough water to bring the uppermost soil strata to **field capacity** (the amount of water that can be held against gravity). This means that there is a wetting front as well as a drying front and both move downward.

The general result of these phenomena is that the ecological and silvicultural rules that govern the lives of new seedlings are quite different from those that apply later on. If the amount of competing vegetation is reduced, such as by thinning, the supply of water for established trees is increased. On the other hand, reduction of overstory vegetative cover during the early and most crucial stages of regeneration reduces the water supply for new seedlings and also threatens them with microclimatic extremes of solar radiation and temperature that are of little consequence once seedlings have become well established. If this distinction is overlooked, it can be very puzzling by seemingly paradoxical results of why seed does not germinate or very young seedlings die, but the established seedlings grow well.

Although there are exceptions, the seedlings of most tree species cannot colonize severely exposed microsites of compact bare clay-textured soil without the protective cover of hardy pioneer herbaceous vegetation. Sometimes this herbaceous vegetation is so ephemeral that it is taken for granted or is overlooked because it soon vanishes, leaving only the small trees that it once sheltered. The seeds and seedlings of many tree species have adaptations to take advantage of such cover.

The cotyledons and juvenile foliage of new tree seedlings are often built or arranged in ways that make them more shade tolerant or efficient in photosynthesis than foliage of the adult stages. The seeds of many trees (e.g., oak, hickory, walnut) have enough stored material that they are more dependent on water to mobilize these reserves than on their own initial photosynthesis. The supply of carbon dioxide for photosynthesis is quite large because of close proximity to the respiring

organisms that feed on soil organic matter. The supply of light becomes much more crucial later on, but even then the requirements and adaptations of different species vary tremendously (Tables 5.5, 5.6). The availability of soil nutrients usually does not limit the growth of new seedlings. The seeds themselves supply some nutrients, and more are usually released by the decay of the plants that were killed to make the regeneration vacancy in the first place.

Provisions for Initiating Natural Regeneration

Successful regeneration of any sort, natural or artificial, can occur only if the right amount and kind of growing space becomes available for the establishment and subsequent growth of the desired species (Fig. 5.9). The ideal objective is to create open space that is not merely favorable to the desired species but is more favorable to them than to any others.

Regulation of Regenerative Canopy Openings

In very small openings, the development of extreme surface temperature is impeded by side shade. In large openings, the wind causes enough turbulent transfer of heat to restrict the diurnal range of surface temperature. There is evidence that the greatest extremes of temperature occur when the diameter of an opening is 1.5 times the height of the surrounding trees (Geiger, Aron, and Todhunter, 1995). Presumably this is the situation in which the combined effect of side shade and ventilation is the lowest.

When an opening is more than two to three times the height of the surrounding trees, the environmental conditions at the center are about the same as those that would prevail in any much larger opening (Minckler and Woerheide, 1965; Geiger, Aron, and Todhunter, 1995). Some important things that would differ, however, would be the effectiveness of seed dispersal from the adjoining trees and effects of travel of seed-dispersing animals between the opening and the cover of the taller trees.

Climatic differences between microsites can also be systematized in terms of the distinction shown in Fig. 5.6a between conditions found: (1) in unshaded, open areas; (2) in the side shade and partial protection of uncut timber along the edges of openings; and (3) under full shade (Ashton, 1992b; Balisky and Burton, 1995; Gray and Spies, 1996). The edge zone is exposed to the scattered diffuse light from the sky but not to any harmful effects of direct sunlight. Although the total amount of light is distinctly reduced, diffuse radiation is relatively rich in the blue wavelengths most effective in photosynthesis. This transitional zone extends, for practical purposes, from the fluctuating edge of an uncut stand outwards, as well as a short distance inward beneath standing trees. The illumination under full overhead shade, consists of whatever direct sunlight penetrates through interstices in the crowns, as well as light that is rich only in photosynthetically useless green and infrared wavelengths that are transmitted through the foliage. The differences between these zones correspond to

Table 5.5 Attributes of trees that change in relation to amount of light for shade-intolerant and shade-tolerant trees, with attributes organized in order of increasing scale from leaf to stand.

	Shade intolerant	Shade tolerant
Leaf morphology		
Individual leaf area	Low	High
Leaf orientation	Erect	Horizontal
Leaf thickness	Thick	Thin
Cuticle thickness	Thick	Thin
Palisade mesophyll thickness	Stacked and high	Single-layered and thin
Palisade/spongy mesophyll ratio	High	Low
Stomatal size	Small	Large
Stomatal density	High	Low
Leaf physiology		
Light saturation rate	High	Low
Compensation point	High	Low
Stomatal conductivity	High	Low
Water-use efficiency	High	Low
Nitrogen-use efficiency	High	Low
Crown morphology		
Leaf area index	High	Low
Branch orientation	Erect	Horizontal
Branching pattern	Whorled and upward	Branching and planar
Whole plant morphology		
Allocation to leaves	Low	High
Allocation to roots	High	Low
Bole taper	Low	High
Live crown ratio	Low	High
Reproductive effort	High	Low
Seed size	Small	Large
Self-pruning	High	Low
Stand dynamics		
Self-thinning	High	Low
Stand density	Low	High

Source: Mark S. Ashton.

Table 5.6 Shade tolerance rankings of some North American tree species in eastern and western American forests.

Relative shade tolerance	Eastern American trees	Western American trees
Very tolerant	Eastern hemlock	Western hemlock
	Balsam fir	Pacific yew
	American beech	Vine maple
	Sugar maple	
Tolerant	Red spruce	Western redcedar
	White spruce	Grand fir
	Northern white-cedar	Mountain hemlock
	Red maple	Redwood
		White fir
		Bigleaf maple
		Tanoak
Intermediate tolerant	Atlantic white-cedar	Western white pine
	Eastern white pine	Sugar pine
	Bald cypress	Douglas-fir
	American chestnut	Giant sequoia
	Hackberry	Pacific madrone
	Yellow birch	
	Black birch	
	Shagbark hickory	
	Water hickory	
Intermediate intolerant	Slash pine	Engelmann spruce
	Northern red oak	Subalpine fir
	Live oak	Sitka spruce
	Shumard oak	Oregon ash
	Swamp white oak	California black oak
	American elm	
Intolerant	Red pine	Limber pine
	Pitch pine	Pinyon pine
	Loblolly pine	Ponderosa pine
	Shortleaf pine	Lodgepole pine
	Cherrybark oak	Whitebark pine
	Nuttall oak	Western larch
	Pine oak	Red alder
	Post oak	Paper birch
	Scarlet oak	
	Black cherry	
	Sweetgum	
	Pignut hickory	
Very intolerant	Black locust	Black cottonwood
	Longleaf pine	Quaking aspen
	Jack pine	
	Quaking aspen	
	Eastern cottonwood	

Source: Mark S. Ashton.

(a)

(b)

Figure 5.9 Ponderosa pine regeneration under difficult climatic circumstances in northern Arizona. Figures **(a)** and **(b)** show the same spot just after a group-selection cutting in 1909 and again in 1938. The saplings of the second picture did not become established until abnormally favorable circumstances took place in 1919. Unusual May rains probably overcame the competitive effect of the grass cover. *Source:* **(a, b)** US Forest Service.

different degrees of root competition, except that sunlit edges on the northern sides of openings in the northern latitudes are almost at full light but have greater root competition (Gray and Spies, 1996).

However, Fig. 5.6 does not depict the more complex patterns in which forest cover is opened to create vacancies for regeneration that create a diffuse cover of scattered trees, such as that which might be left in uniform

shelterwood cutting. Such cutting would theoretically allow more ventilation and narrow the extremes of surface temperatures. This kind of cutting is the best way of increasing the area of the edge zone and virtually eliminates the full shade zone but puts varying amounts of surface into the open zone.

Some useful ideas about controlling regeneration from seed can be deduced by observing the patterns of species and their height growth in different parts of forest openings (Denslow, 1980; McClure and Lee, 1993; Smith and Ashton, 1993; Ashton, Gunatilleke, and Gunatilleke, 1995). These things can be observed and diagnosed most simply in circular openings, as shown in Fig. 5.10. The same can be observed in openings of any shape but is not as simply analyzed. Quantities of light received beneath forest cover vary with size of opening and position beneath the opening. In a circular opening, those effects associated with the slanting rays of direct solar radiation will be arranged in crescentic patterns. Those effects controlled by root competition of adjoining vegetation, diffuse solar radiation, air movements, and outgoing radiation (frost and dew) should have concentric arrangement. Except for the effects of root competition because of the power of direct sunlight, crescentic patterns are much more common than concentric patterns. However, these patterns will be altered by the degree and aspect of slope and by latitude. At low latitudes around the equator, direct solar radiation can be received at both north and south edges depending upon time of year, and given no strong seasonality. Annual amounts of direct solar radiation should then be about the same, thus giving a concentric pattern. Because there is no environmental factor more readily predictable than the sun, the extent of side shade can be calculated for each slope, aspect, and latitude (Canham, 1988; Rich *et al.*, 1993).

On pole-ward slopes, all shade zones are broadened, and the steeper the slope, the more they are broadened. On equator-ward slopes these effects are the opposite. At high latitudes, the various shade zones become very broad; diffuse solar radiation may even become fully as important as the direct. In the tropics, most such patterns become concentric, and side shade is effective only in very narrow bands. Usually the only place where new seedlings of species that are tolerant of shade and intolerant of exposure can appear is in a crescent along and under the southern edge. This is common at mid-latitudes of the Northern Hemisphere (Fig. 5.10). More shade-intolerant and exposure-resistant species find their optima for establishment and height growth in crescents arranged successively northward (Smith and Ashton, 1993; Liptzin and Ashton, 1999; Duguid *et al.*, 2013). At the very northern edge there is often a peculiar zone, almost like a little desert, in which the combination of unimpeded direct sunlight and root competition of taller trees can prevent much of anything from regenerating.

Therefore, the sizes of the vacancies created in the growing space should be neither so large that the desired seedlings are overwhelmed by new undesirable vegetation nor so small that they are overtopped by preexisting vegetation expanding from the sides. Excessively heavy cutting or overly drastic site preparation can facilitate too much unwanted pioneer vegetation. Openings can also be so small that they create no real vacancies in the soil growing space. If intraspecific root grafts exist, the root systems of the trees that were cut may simply be taken over by those of adjacent uncut trees of the same

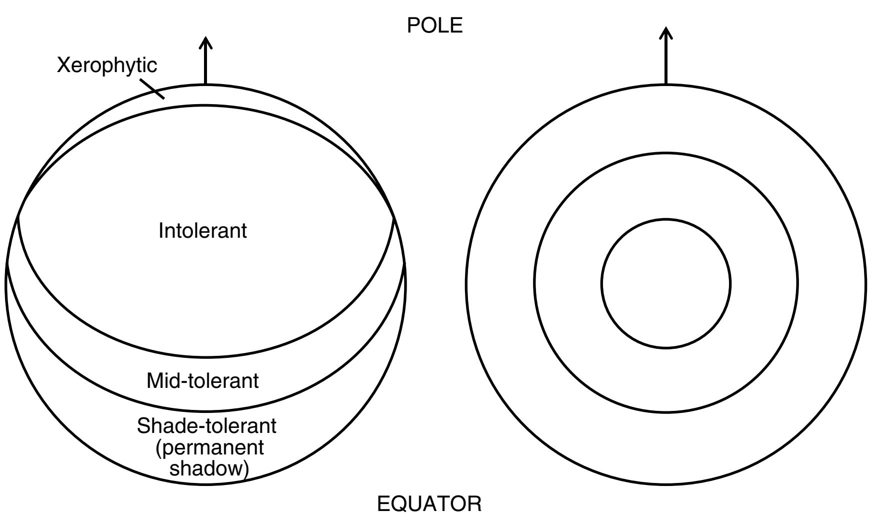

Figure 5.10 Crescentic (left) and concentric (right) patterns of horizontal variation in the effects of microclimatic factors in circular openings at some mid-latitude. The kinds of species favored by different kinds of shading and exposure are indicated in the crescentic pattern caused by direct solar radiation. Concentric patterns due to diffuse solar radiation and long-wave radiation (e.g., frost) are more likely to appear during the development of established vegetation than to affect species composition. Recognition of these two kinds of microclimatic variation may help in deducing the factors governing regeneration and determining how to control it. *Source:* Yale School of Forestry and Environmental Studies.

species. Even more commonly, the roots and crowns of adjacent trees expand into the vacancies faster than the newly established trees can claim them. This can be deceptive because roots, which do not have to provide for their own mechanical support, often expand into vacancies faster than the more visible crowns (Palik *et al.*, 1997). This kind of effect is most spectacular on sites where soil moisture is so limiting that a stand may fully occupy the soil without ever achieving full closure of the crown canopy. Examples of this are particularly apparent in the western US with the ponderosa pine and pinyon–juniper woodlands.

The size and shape of an opening are limited by requirements for a supply of seed from adjacent trees. It is not absolutely necessary that openings be created all at once because they can be enlarged in a series of operations. This sequence is often useful for species that can become established only under some sort of shelter, yet will not commence rapid growth without release. Natural regeneration is easy if any species that appears is acceptable and the site is not marginal for natural tree growth. It becomes more difficult when one seeks some chosen species or wants very prompt establishment. One of the keys to controlling the process is understanding the adjustable microenvironmental phenomena that govern where given species will appear.

These patterns are greatly modified by differences in seedbed conditions that can vary considerably from microsite to microsite. Close-by shade of stumps, rocks, and woody debris can also be as effective as that of more distant tall trees. Furthermore, after shade-intolerant seedlings or saplings are established, seedlings of shade-tolerant species can start beneath them. The height growth of these shade-tolerant individuals is likely to be slow until the trees above them are eliminated. The patterns can also be obscured and confused in nature by preexisting advance growth and vegetative regeneration, that are already present when the opening was created. Observations of these patterns can help greatly in deducing the microsites that a forester would aim to create over larger areas to produce stands of the desired species composition. The desired spatial pattern will then usually be different from the circular openings that are ideal for our descriptive use in this chapter.

From these considerations it can be deduced that even small forest openings cannot be regarded as uniform habitats for regeneration. If the regeneration in a half-acre (quarter-hectare) opening is all lumped together and counted collectively without regard for spatial variations, as much useful information will be buried as is revealed.

Regulation of the Groundstory

Unlike the understory which describes all tree strata below the forest canopy, the **groundstory** is the part of the vertical forest profile that includes the ground surface and the plants that are less than 1 ft (<0.25 m) above. The stratum of the groundstory is therefore the most suitable scale and focus for initiating and observing regeneration. In silvicultural practice, appropriate kinds of regeneration environment are created partly by regulating the pattern in which the previous stand is removed. Most of the names of regeneration cutting methods discussed in later chapters refer to these patterns. Differences among these methods are so visible that they tend to dominate thinking about regeneration treatment.

However, the pattern of tree removal falls far short of being the only factor that controls regeneration. It is also frequently necessary to regulate the lesser vegetation that can either compete with or favor the desired species. This includes not only the vegetation that is already established, but also that which may appear in response to the regenerative disturbance (Fig. 5.11). If it is undesirable, it cannot be wished away by single-minded concentration on the desired tree species.

Sometimes regeneration, especially that from seed, is regulated by various treatments of the soil and the forest floor (see Chapter 7 on site treatments) (Palik *et al.*, 1997; Gray, Spies, and Easter, 2002). The physical characteristics of the surfaces on which germination takes place exert a powerful control on seedling establishment. Very small differences can cause remarkable variations in the species of plants that appear. The physical characteristics of the soil in relation to extremes of temperature and water loss were discussed in greater detail in the section “Surface Temperature and Energy Transfer” earlier in this chapter. These treatments are most relevant for regeneration originating from small seed associated with lethal disturbances because, without the parental endowment of large seeds, small seeds are immediately dependent on a suitable high light and moist soil microenvironment to successfully photosynthesize and take up water. Regeneration by planting and from vegetative sprouting evades most of the crucial problems involved in the germination and establishment stages. These forms of regeneration are not immune to microenvironmental effects but are not so tightly regulated by them.

Disturbance, Climate, and Regional Patterns in Floristics of Forest Regeneration

The focus so far has been on describing the principles in understanding the role of disturbance in securing regeneration and the regeneration process itself. Now, some examples of regeneration composition and pattern in relation to disturbance will be provided, describing the relationships between different kinds of disturbance and regional climates and forest types.

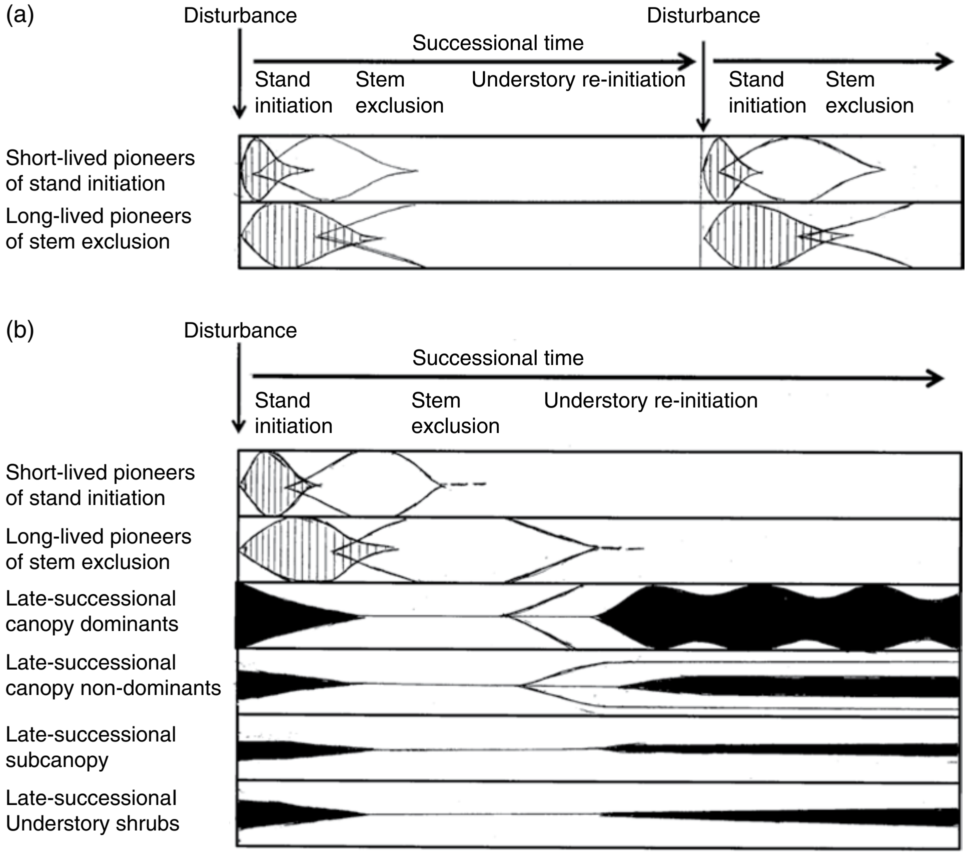

Figure 5.11 Recruitment frequency and pattern of regeneration of different functional and ecological species groups over the different stages of stand development after an initiating disturbance. Each of the horizontal graphs (kite diagrams) shows the time of appearance and the changing abundance of each of the different groups of species that are listed adjacent their respective diagram. Vertical hatching depicts regeneration of pioneers that establish immediately after a disturbance. The solid black depicts species groups that rely on advance regeneration established before the disturbance and subsequently released. Note that advance regeneration re-establishes again when the seedlings that were released post-disturbance eventually attain the canopy, and they become reproductively mature (understory reinitiation). The white lines post-ceding the regeneration recruitment event for each species group represents when the seedlings that establish or are released attain canopy dominance in the forest. The breadth of the line defines dominance. For example the short-lived pioneers achieve canopy dominance first, then the long-lived pioneers and then late-successional canopy trees. Depictions are shown for: **(a)** a moist temperate (e.g., oak–maple–hardwood) or tropical forest dominated by release-type disturbances (note dominance of advance regeneration); and **(b)** a boreal interior forest (e.g., jack pine) dominated by lethal-type disturbances (note absence of advance regeneration). *Source:* **(a, b)** Mark S. Ashton.

In almost all forest regions, natural succession and development of new stands proceed either from already established survivors, or from the germination of seeds (Connell and Slayter, 1977; Glenn-Lawson, Peet, and Veblen, 1992). This occurs almost immediately after a disturbance has liberated or created new growing space. However, the complexity and variety of ecological species groups (Bazzaz, 1979; Swaine and Whitmore, 1988; Whitmore, 1989) and their inherent differences in reproductive mechanisms (Grubb, 1977) will vary because climates and the disturbance regimes they create are different across forest regions (Oliver and Larson, 1996; Turner *et al.*, 1998; Dale *et al.*, 2001). For example, in many moist forest regions, the kind and variety of regeneration that appears after a release disturbance that kills only some of the forest canopy and does not harm the groundstory can be very complex and diverse in nature (Fig. 5.11b). This is because many forms of advance regeneration and vegetative sprouts, already present in the understory before the occurrence of a disturbance, are allowed to survive. On the other hand, more severe lethal disturbances can promote a more uniform and simpler species composition that comprises a higher proportion of pioneers, with ecological species groups that are more reliant on strategies that occupy newly available growing space (Fig. 5.11a) (Dale *et al.*, 2001). Thus it is important to recognize that the origin in the stand of both structural and dynamic complexity is established at the regeneration stage. The simpler forest types with lower numbers of tree species and less complex structures are associated with the more lethal disturbance regimes.

Fire, Wind, and Water

The Role of Fire as a Disturbance

Fire is one of the most common kinds of natural disturbance, and many species, including some of the most valuable to the North American forest, represent natural adaptations of vegetation to fire (Pyne, 1984; Agee, 1993; Koskela, Kuusipalo, and Sirikul, 1995). Fire, by itself, generally kills small trees more effectively than large ones. It therefore tends to kill old stands from the bottom upward. However, except for landslides, volcanic eruptions, and similar geologic events that set off true primary succession, the most severe natural disturbance of forests is usually a sequence of blow-down or insect kill followed by a hot crown-fire. Such fires have tremendous amounts of dead, dry fuel (Stocks, 1998; Schoennagel, Veblen, and Romme, 2004). The regeneration of some species appears to require the simulation of these kinds of fires. One of these is *Eucalyptus regans* of southern Australia, which grows faster and almost as tall as coast redwood. A lower stratum of non-eucalypt understory has to be felled to produce enough fuel to get fires of required intensity to successfully regenerate to *Eucalyptus regans* (Stoneman, 1994). A view has been advanced that some species have evolved to produce enough fuel to provide for their own pyrogenic renewal.

Forest types with fire-fostered species can be considered to have five ecological species groups depending on the nature of their adaptation to fire (Table 5.7). The closed-cone pines constitute the first group. They are best exemplified by jack pine and include lodgepole, Monterey, bishop, and sand pine. In these species, regeneration occurs naturally after a hot ground and crown fire has killed the trees, exposed the mineral soil, and opened the cones (Turner, 2010).

The second group is composed of species like the cherries and a number of shrubs (e.g., *Rubus*), including certain species of *Ribes*, which have hard-coated seeds capable of surviving for long periods in the floor and springing up after fires.

The third category consists of light-seeded species that thrive on seedbeds of bare mineral soil exposed by fire but are not outstandingly resistant to fire. This group includes many valuable species such as the birches, Douglas-fir, eastern and western white pine, the spruces, sweetgum, and yellow-poplar. Regeneration of these species after fires comes from wind-dispersed seeds already present on the old trees or subsequently produced by trees that happened to survive because of their size or location. This group can contain short- or long-lived pioneers such as paper birch or Douglas-fir, respectively.

The fourth group consists of the large number of species that can reproduce from sprouts. This group is composed mainly of broad-leaved trees (e.g., certain species of oak and eucalypt) and shrubs (often in the rhododendron family), but also includes a few conifers (redwoods). After severe fire, buds below the soil surface survive on the bole of the tree at or below the root collar and sprout afterwards.

In all four categories mentioned so far, the species involved are primarily adapted to regeneration after catastrophic fires that destroy most of the trees of one generation and prepare the way for another. It would be unwise to duplicate these kinds of fires because of public danger. The broadcast burning of slash is sometimes used to simulate these effects, but it is commonly necessary to resort to measures that do not necessarily include any burning at all.

Finally, there is a fifth category of species that have sufficiently resistant bark to withstand burning at intervals throughout most of a single generation. This group consists of certain hard pines, notably those of the southern US, but also larch of the inland west and the upland oaks of the east and west. The most outstanding is longleaf pine, which thrives only as a result of periodic fires. The others are loblolly, pitch, shortleaf, slash, and ponderosa pine. It could be argued that red pine representing sandy fire-prone sites in the upper midwest belongs in this group as well. Occasional surface fires were beneficial to the maintenance of these species in the original forest because they arrested natural succession, exposed favorable seedbeds, and prevented more destructive fires. Up to the present time, prescribed burning has been extensively applied only to this group of fire-resistant trees. It has been practiced on a large scale mainly on the Atlantic Coastal Plain from New Jersey southward. Many species have several kinds of adaptations to fire. Pitch pine, a species that grows on sites where it is constantly bedeviled by fire, is an outstanding example of such a species (Little and Somes, 1961). It develops the thick, fire-resistant bark characteristic of trees of the fifth group. Pitch pine cones have a tendency to be serotinous, like the cones of pines of the first category. Seedlings and saplings killed by fire will sprout from the base, like species of the fourth group, and older trees defoliated by fire usually sprout new crowns.

Another way of viewing differing degrees of adaptation to fire is to note that a given locality may have species with adaptation to different frequencies and severities of fire. In forested climates, sprouting perennial grasses often go with annual burning and sprouting shrubs. With less frequent burning many of the tree species endure such burns (group 5). Sprouting tree species (group 4) are next in line if fires are too frequent for seed production. Serotinous-coned conifers (group 1) or species with seeds that remain stored in the forest floor (group 2) often come next where fires are at more distant intervals and are more severe. Co-equal with these may be the

Table 5.7 Examples of North American forest types and species groups associated with disturbance: fire, water, and wind.

Forest type	Species examples
FIRE	
Fire: groundstory fires that burn frequently (approximately 3–15-year cycle)	
Forest type	**Species examples**
Pine woodlands of the southern coastal plain	Longleaf pine–wire grass
Oak woodlands of the central states and southern New England	Oak–hickory complex
Mediterranean oak woodland	California oak community
Intermountain pine woodland	Ponderosa pine, interior Douglas-fir
Fire: crown fires that are strongly episodic (approximately 80–100-year cycle)	
Forest type	**Species examples**
Interior continental mountain and boreal pine forests	Jack pine, lodgepole pine
Coastal sand plain pine forests of the east	Pitch pine, slash pine, sand pine
Interior continental boreal forest	White spruce–aspen community
Fire: crown fires that are strongly episodic (approximately 200–1000-year cycle)	
Forest type	**Species examples**
Western continental mountain forest	Englemann spruce–subalpine fir
Coastal Pacific Northwest forest	Douglas-fir, western hemlock, western redcedar
Northern hardwoods	Pin cherry–paper birch–rubus
WATER	
Water: frequent flooding (on an annual basis)	
Forest type	**Species examples**
Coastal swamp forests of the southeast	Tidal mangroves
Lacustrine and estuarine backwater forests	Bald cypress
Floodplain forest of the south and Gulf coast	Bottomland hardwoods
Water: episodic flooding (irregular decadal to centennial events)	
Forest type	**Species examples**
Beaver meadows	Red maple swamps
Riparian forests of big rivers of the east and west	Cottonwood–willow
Riparian forest of coastal Pacific Northwest	Sitka spruce–red alder
WIND	
Wind: frequent small windthrows and convectional storms (annually)	
Forest type	**Species examples**
Appalachian hardwoods	Eastern hemlock, beech, maple, yellow-poplar
Northern hardwoods	Beech–sugar maple–yellow birch
Maritime boreal of northeast Canada	Red spruce–balsam fir
Wind: episodic events, hurricanes, tornadoes, and convectional storms	
Forest type	**Species examples**
Allegheny hardwoods	Hemlock, black cherry, sugar maple
Coastal pine hardwoods on the east coast	Loblolly pine–oak–sweetgum

Source: Mark S. Ashton.

pioneers with long-distance seed dispersal or the fire-resistant species that regenerate after light fires have burned beneath them (group 3). Next are usually those that regenerate after fires at very long intervals, often under the protective cover of some simultaneously regenerating pioneer (group 3). The final members of the series are those that are simply so defeated by fire that they can return only after some intervening stages of succession. Not all members of such a series exist in a locality, but it is useful to know for each locality, what species would be fostered by a given frequency and severity of fire.

The Role of Wind as a Disturbance

Wind and its interactions with cold and precipitation create the most diverse array of disturbance regimes that impact forests and woodlands of the world (see Table 5.7). Winds and their scale, type, and frequency are associated, like fire, with regional climates and topographies (Pickett and White, 1985; Aber, 2001). As mentioned at the beginning of this chapter, the combinations of wind and desiccating cold create the fir-wave phenomenon that is the most important disturbance driver of many montane temperate forests (e.g., White Mountains of New England, Cascade Range of western Washington) (Sprugel, 1976; Smith, 2000). Hurricanes, typhoons, and cyclones are all strongly seasonal and usually impact the eastern coasts of continents (e.g., eastern US and the Caribbean, northeastern Asia, eastern India, and the Bay of Bengal, and northeastern Australia) (Oliver, 1980; Frelich and Lorimer, 1991; Boose, Foster, and Fluet, 1994). They are generally strongest and most frequent around 23 degrees north or south of the equator, and weaken and are less frequent on going northward. Tornadoes are a North American experience, most associated with strong frontal storms in the US midwest during spring. Similarly, and more commonly, convectional downbursts occur during summer months when cold frontal systems move violently in to replace hot and humid air that has built up over a region. All these kinds of winds are affected by their origin and direction, by the presence or absence of preceeding or concurrent precipitation and by topography. This affects the nature and kind of floristic associations found across topography within a forest type (Figure 5.12) (Molino and Sabatier, 2001). Using the terminology in prior sections of this chapter, wind would be considered a release disturbance in almost all circumstances because it tends to remove the overstory with little impact to the groundstory.

Wind in all its variations is the most important driving disturbance regime across upland moist or wet temperate and tropical climates where fire is not very prevalent. Because of this, forests originating after wind disturbances can be considered to have tree species categorized into five ecological species groups (see Fig. 5.11). The first group can be considered tree species that rely upon advance reproduction in the form of seedlings or seedling sprouts. This is the traditional and dominant ecological group for forests of wet climates. Most of the large late-successional trees in the forest belong to this grouping. Species in this group rely upon securing growing space as seedlings at the groundstory beneath closed canopied forest before a disturbance occurs. This means that species in this group have an ability to endure shade, though this can vary between species and in relation to site (Fig. 5.12). Two subgroups can be considered: (1) those that mast strongly with super-abundant seed on occasional years with other years producing almost nothing; and (2) those that produce a steady but relatively small number of fruits and seeds per year.

Species that mast often can be considered to belong to an older lineage in co-evolution with animal dispersers. Obvious masting families are those that produce nuts such as the tree families *Fagaceae* (oaks, chestnuts, beeches), *Pinaceae* (pines, firs, spruces), *Dipterocarpaceae* (luan, meranti, Philippine mahogany, sal) and *Juglandaceae* (walnuts, hickories). Whether or not masting is related to climate, it is strongly regulated by the animal populations (especially rodents) that rely upon the nuts as a caching food source (Kelly and Stork, 2002). However, when seed consumers are unable to eat all seeds present in a year of super-abundance, many seeds germinate and establish together as a strong cohort that can persist in a forest understory for years with little growth. This hypothesized method of dispersal has been referred to as predation saturation. For example, oak advance reproduction in New England still persists in the understory from the mast years of 1993–1994 and is an important source of regeneration for new stands (Frey *et al.*, 2007). Dispersal is limited, remaining close to the parent tree, because animal dispersers are territorial (e.g., rodents) and do not travel great distances. The exception to this are birds (e.g., jays, nutcrackers) which are very effective seed dispersers that can cache masting seeds miles away. This means that carpets of seedlings all of the same age will germinate beneath the parent tree. The seed is susceptible to predation, but after germination, the seedlings are practically inedible because of their high tannin and phenol contents. At this point, they are usually well protected from herbivores. Species that mast can make up complex congeneric assemblages with each species stratifying by site. They are thus site restricted but dominate as clumped associations across the topography (Fig. 5.13). Many studies have shown species within this subgroup to have close association with particular soil moisture and nutrient regimes.

The second subgroup consists of heavy-seeded species that place a lot of reproductive effort in fruit quality. Species in this subgroup usually have a more sophisticated co-evolutionary relationship with their animal

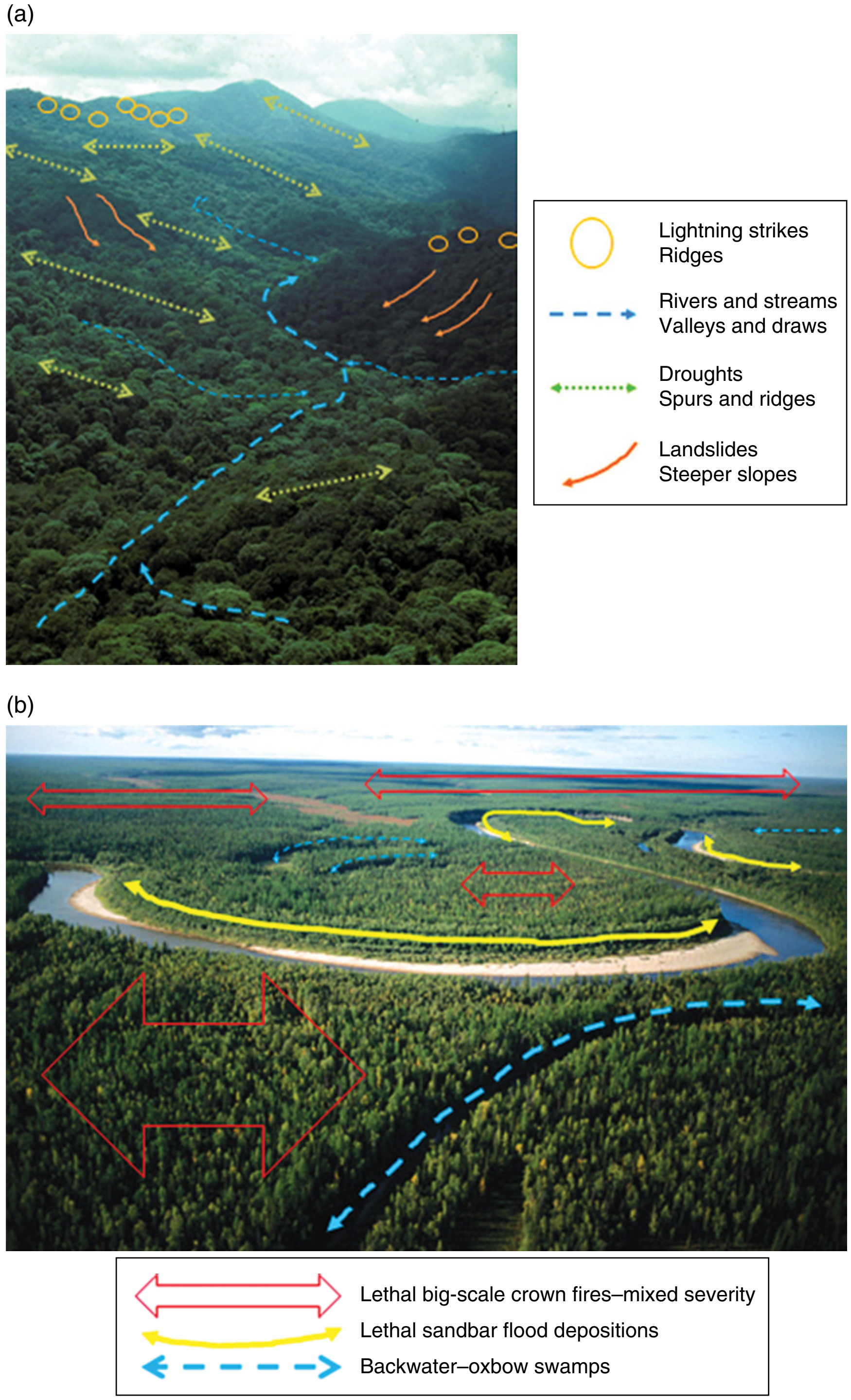

Figure 5.12 Illustrations of change in disturbance scale, type, and intensity, across different topographies. **(a)** Southwest Sri Lanka in mixed dipterocarp forest. **(b)** Interior boreal spruce–aspen forest, Canada. *Source:* **(a, b)** Mark S. Ashton.

seed dispersers: *Ebenaceae* (persimon, ebony), *Lauraceae* (avocado), *Anacardiaceae* (mango). The fruit and pulp around the seed is usually rather large. The seed in this case is the by-product rather than the incentive, and is either passed whole through the gut or discarded. Large animals (primates and large birds like toucans) that disperse these fruits will do so, far and wide, given their wide-ranging territories. As such, the seed is very effectively dispersed away from the parent tree and germinates as a single individual surrounded by unrelated taxa. Success at further distances is not because the species can avoid distributing seeds near the parent, but rather because those seeds that are more widely dispersed manage to escape the negative consequences of growing near the parent from effects of pests and pathogens. This hypothesized effect is known as negative density

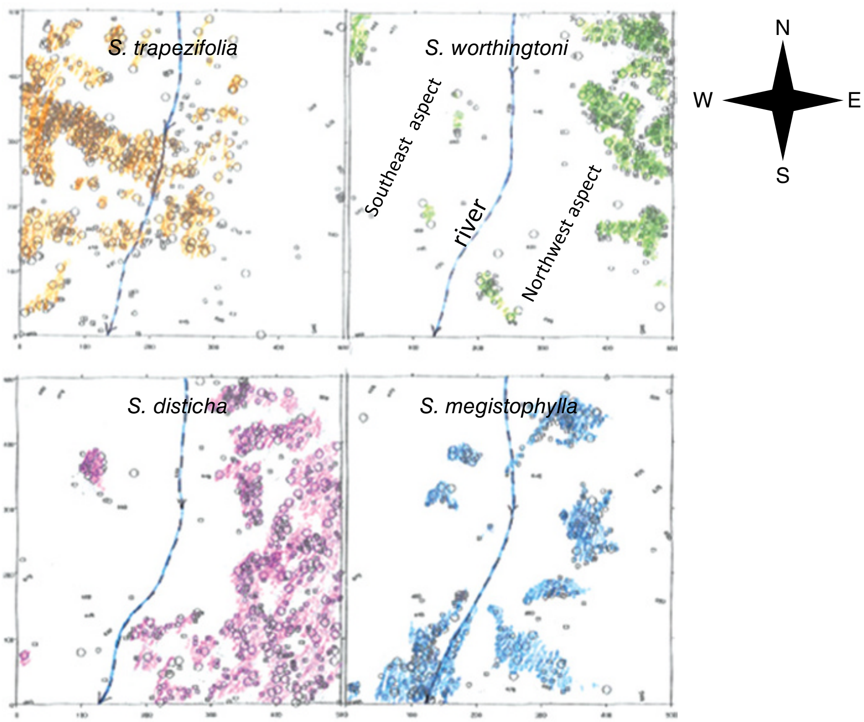

Figure 5.13 Species demographics as depicted by stem distributions in a 62 acre (25 ha) spatially explicit plot for four site-restricted *Shorea* spp. for a tropical rainforest in Sri Lanka. The topography is sloped with a river bisecting the plot from north to south and slopes away from the river with northwest and southeast aspect. *Shorea trapezifolia* (orange) chiefly occupies the southeast aspect while *S. disticha* (pink) occupies most of the northwest slope; *S. megistophylla* (blue) is restricted to the lower lying riparian areas and seeps; *S. worthingoni* (green) is restricted to the ridges and spurs on the northwest aspect. *Source:* Mark S. Ashton.

dependence, meaning that progeny do better away from, rather than closer to, their parent trees because they are susceptible to the same pathogens, predators, and herbivores (Wright, 2002; Volkov *et al*., 2005). Trees in this group are thus well dispersed but do not dominate stand densities or basal areas of local areas. Effectively dispersing away from a parent tree obviously promotes species in this group to be more site generalists capable of germinating on a range of forest understory sites and soils. Both subgroups produce large seed with high water content and stored carbohydrate, making them shade tolerant. They would be considered recalcitrant, germinating almost immediately in tropical moist conditions or after one brief winter in temperate moist climates.

The second category of regeneration is that which regenerates vegetatively. Again, species in this group rely upon disturbances that do not kill the rootstock of the original plant but allow the roots to survive, sprout, and spread. In moist temperate and tropical forests the subcanopy trees *Clusiaceae* (mangosteen) and understory shrubs *Ericacaeae* (rhododendron) and *Rubiaceae* (coffee) belong to this category. Many of these species grow in low-light conditions, meaning that carbohydrate allocation goes to protection through chemicals at the expense of growth. Flowering in light-limiting circumstances is weak with stronger reliance on self-pollination. However, given a disturbance to the canopy, vegetative release can be prolific and fast with a propensity over time to create clonal understories that often can impede advance regeneration of late-successional canopy trees (group 1).

The third category includes the fast growing, shade-intolerant pioneers which all produce small numerous seeds that are dispersed either by wind, small birds, or bats. In doing so these seeds germinate and establish after a disturbance occurs and thus have to occupy ground which has been disturbed enough to have destroyed any advance reproduction and killed any roots and stems that can reprout. Two subgroups can be described: (1) those short-lived pioneers that germinate immediately in open growing space and grow fast to provide a relatively short-statured umbrella-shaped crown; and (2) those long-lived pioneers that can grow in dense stands together with strong monopodial branching and columnar crowns (Swaine and Whitmore, 1988; Whitmore, 1989).

The short-lived pioneers *Moraceae* (Macaranga), *Anacardiaceae* (sumac), *Rosaceae* (pin cherry), *Betulaceae* (gray birch), and *Salicaceae* (willows) seed both frequently (yearly) and prolifically into open growing spaces as seed rain, which is wide ranging and random. Seedlings grow very fast but are weak, with low-density wood that often collapses with the weight and spread of the crowns. Species also produce large leaves, transpire freely, and have superficial surface root systems that usurp nutrients that may be leached and lost with erosion after a disturbance. These species are therefore very efficient colonizers of open growing space. The long-lived pioneers *Meliaceae* (mahogany) and *Pinaceae* (pines, firs, Douglas-fir) often exhibit a masting tendency, and do not travel as far from the parent tree.

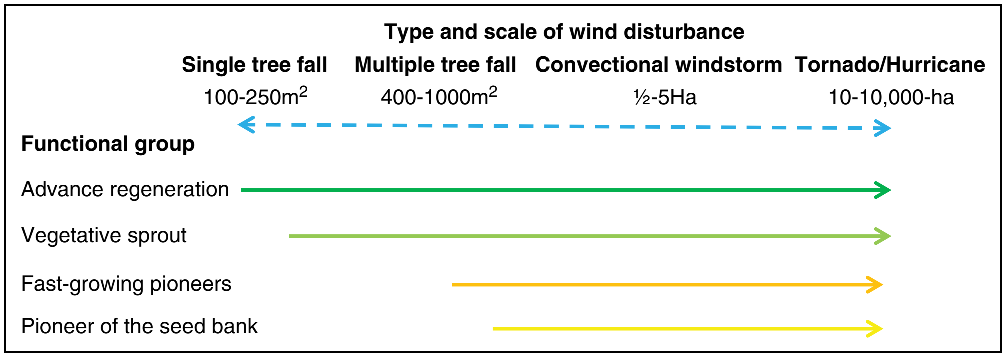

Figure 5.14 Diagram depicting reproductive presence of four ecological groupings in relation to size of wind disturbance to the forest canopy. *Source:* Mark S. Ashton.

These trees grow well in dense mono-dominant stands and grow with straight boles (Whitmore, 1989).

The fourth and last category comprises pioneers that are stored as a soil seed bank. Many of these species immediately germinate when soil conditions are exposed to heat and sun. Most include fast-growing herbaceous and shrub species (e.g., *Rosaceae, Rubus)*. Seeds are small and hard coated and can store themselves after dispersal for many years in the surface duff layer of the soil, waiting for a disturbance.

Taken together, all four categories of regeneration vary in dominance depending upon degree of severity and size of opening. The smaller and less severe the opening, the greater the degree of domination of shade-tolerant advance growth. The more severe and open the disturbance, the more the shade-intolerant pioneers dominate. Disturbances that create microsite heterogeneity, such as multiple windthrows and partial canopy removals, create the greatest diversity and range of regeneration (Fig. 5.14).

Water as a Disturbance

Water as a disturbance mechanism is localized to the floodplains, estuaries, and coastlines of any forest type and climate. Disturbances can be either release or lethal in nature, depending upon the degree of severity and the adaptability of the vegetation impacted. The vegetation itself can be categorized into three groups. The first group includes species which can endure frequent annual or seasonal flooding of backwaters or riparian zones. These species have root systems that can withstand such disturbances and that quickly vegetatively resprout. Examples are shrubs (alders, willows). However, where rivers change course and new sediments are laid down, short-lived pioneers, either dispersed by wind or water, can quickly colonize the open land. These species can be considered to include the second group (sycamores, cottonwoods). The third group of trees is specialized to bogs and swamps. These tree species can be very long lived with a capacity to regenerate as advance growth on hummocks and tip-up mounds or to vegetatively spread through layering. Examples are cypress, black spruce, and Atlantic white cedar.

Regeneration Methods as Analogs to Natural Disturbance

Methods that rely on establishing and releasing propagules of both seed and vegetative origin from sources within or adjacent to the stand being regenerated have been termed natural regeneration methods. In these methods, forest canopy manipulations are carried out to favor or discourage certain kinds and amounts of propagules (Fig. 5.15). These manipulations should, where possible, emulate the type and size of a natural disturbance that achieves the same results (Bergeron *et al.*, 1999; Harvey *et al.*, 2002; Angelstam, 2009).

As previously discussed, two major kinds of natural disturbance, lethal and releasing, define the major differences among the natural regeneration methods: clearcut, coppice, seed tree, and shelterwood. Thus, it is important to consider the name of the method by its predominant origin and guild of regeneration rather than the appearance of the cutting pattern.

True clearcut regeneration methods reflect severe disturbance regimes that remove the preexisting vegetation completely. Regeneration depends on dormant propagules that are in the seed bank or that come in on suitable microsites by wind, water, or animal vectors in large amounts from adjacent stands. Examples of natural disturbances that clearcuts emulate are catastrophic fires and landslides. Seed-tree methods rely upon the same kinds of disturbance environment as true clearcuts, but the focus is on obtaining regeneration of long-lived pioneers with poor seed dispersal. Shelterwood and coppice methods reflect releasing disturbances that depend on propagules that are established *in situ* as advance reproduction (seedlings, seedling sprouts) or are of vegetative origin, respectively (stump and root sprouts).

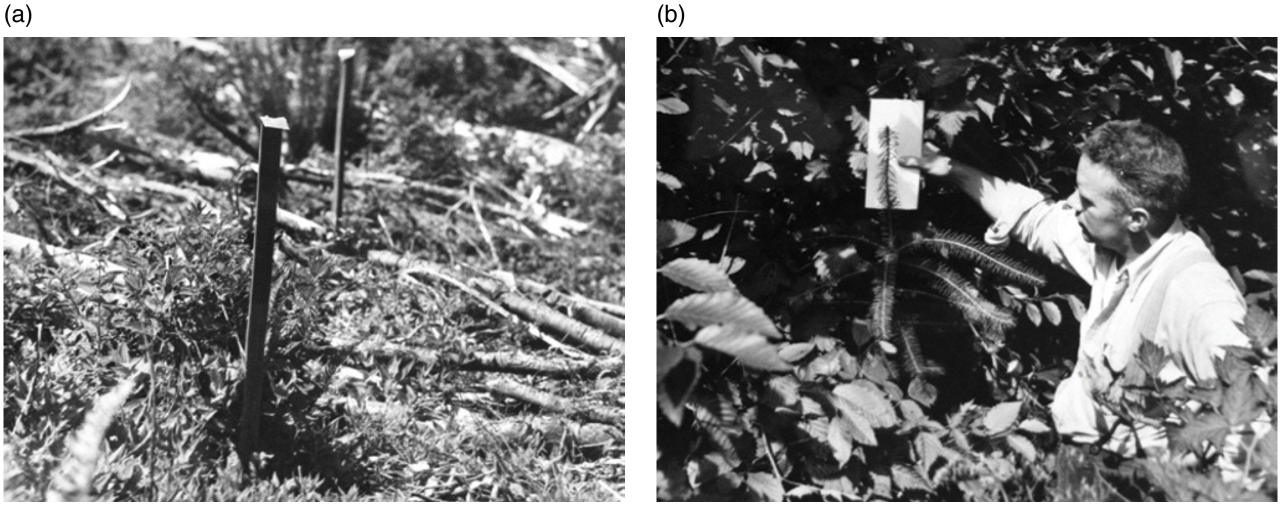

Figure 5.15 In regenerating forests it is necessary to anticipate the development of all the vegetation and not just that of the desired species. (a) A Douglas-fir seedling barely visible in front of a stake during the year after a cutting in a forest on an excellent site on the Oregon Coast. (b) The same tree 3 years later and almost submerged by red alders and thimbleberry bushes that were not apparent earlier. *Source:* (a, b) US Forest Service.

Coppice methods rely largely on bud formation and release of vegetative shoots from parts of the residual vegetation that remain alive after a disturbance. As such, this is a very dependable mode of establishment because a new plant never actually has to colonize vacant growing space in the soil. Canopy manipulations for seed tree and shelterwood are tailored to favor regeneration presence and establishment of seedlings and seedling sprouts before complete canopy removal above the microsite. Differences between seed tree and shelterwood, as the names imply, relate to differences in shade tolerance of the species that are being regenerated. Species that are regenerated by seed-tree methods rely on a parent canopy only for adequate dispersal of propagules. Shelterwoods cater to species with propagules that require both adequate dispersal and microsites that provide partial shade for germination and establishment.

All four regeneration methods emulate natural disturbances at the scale of the stand. This differs from selection methods that can reflect any of the disturbance regimes and regeneration methods described, but are done at much smaller scales within a stand and are repeated continuously across the whole stand during the course of its development. Site treatments to the ground surface, which are discussed in further detail in Chapter 7, also reflect the fundamental differences between severe and releasing disturbances. When the actual forest floor is disturbed, regeneration that is present can be destroyed. Severity of site treatments often matches the severity of canopy manipulation for method of regeneration. The most intensive site treatments are therefore usually done in conjunction with clearcutting; the least intensive are usually done with shelterwood cutting.

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Part 3

Methods of Regeneration

Understanding silvicultural systems, affiliated site treatments, and their methods of natural and artificial regeneration.

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

6

Development of Silvicultural Systems and Methods of Regeneration

Introduction

Systematic programs are required to develop and manage the treatments necessary to create and maintain forest stands for the various goals and objectives desired by landowners and society. The most crucial of these are the various kinds of treatments devised to create microenvironmental conditions favorable to regeneration of the desired species. This chapter introduces programs of treatments and discusses how such programs are formulated to fit management objectives and circumstances of a variety of social and economic values. The main purpose of this chapter is to consider the ways in which silvicultural systems are constructed to deal with the various conflicting objectives.

A **regeneration** or **reproduction method** is a treatment to a stand and its associated species composition and structure in order to to establish or renew it (Barrett, 1995). Each method consists of the removal of all or part of the old stand, the establishment of a new one, and any site treatments of vegetation, slash, or soil that are applied to create and maintain conditions favorable to start regeneration. Any procedure, intentional or otherwise, that leads to the development of a new stand of trees can be called a method of regeneration; sometimes it may be a combination of various methods. A **silvicultural system** is a planned program of silvicultural treatments extending throughout the life of a stand. It includes the regeneration method and any tending operations, protective treatments, or intermediate cuttings that follow or that are conducted in tandem with the regeneration method.

Conceptual Formation of Silvicultural Systems: The Science of Place

A silvicultural system is designed to deal with a whole complex of biological, physical, social, and economic considerations that concern the specifics of a particular forest, stand, or site (Puettmann, Coates, and Messier, 2008). It concerns the tending and manipulation of the growing stock for a range of both compatible and conflicting social and economic values (e.g., wildlife, aesthetics, timber and non-timber products) and the protection of soils, and watersheds. It is also a program for initiating the kind of stand that will produce the desired benefits and for guiding its developmental processes through one or more rotations. Formulation of a silvicultural system should start with analysis of the natural and socioeconomic factors of the situation. A solution is then devised to go as far as possible in capitalizing on the opportunities and conquering the difficulties found to exist. If such programs are not formulated and followed, the management of stands may be governed more by current demands than by any intentions about the future.

For example, shelterwood systems in pine stands might be formulated to produce high-quality lumber, habitat for birds and mammals dependent on the pines, and evergreen shade over snowdrifts to retard spring snowmelt for different landowners. For one landowner, there might be early release of established natural regeneration, followed by pruning, and a sequence of free, crown, and low thinnings designed to maintain rapid diameter growth on some chosen crop trees. These thinnings would merge into shelterwood cuttings for the purpose of establishing partially shaded natural regeneration and setting the stage for repeating the sequence in a new stand. The rotation might be prolonged to provide some old trees for cavity-inhabiting animals and selected groups of occasional canopy trees may be intentionally left to create a greater diversity of habitat and age class for aesthetics and wildlife. There would be shade on the ground continuously if full stocking of new pines was achieved under the old stands. For the second landowner, a less intensive and simpler application of the same system might involve nothing more than final harvest cutting in two stages. In both cases, social circumstance may be different but the goals are the same. In addition, both silvicultural programs might have the same or different steps designed to provide for fire protection, logging safety, supplemental planting, or any of a myriad of other considerations.

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A silvicultural system is therefore designed to fit a specific set of circumstances. It should not be presumed that it is something that has already been invented and can simply be selected ready-made from classifications or schematic descriptions of silvicultural systems. The sweeping prescriptions that have emerged from legislative bodies and courts usually solve one problem at the expense of creating many more. **This book, for example, in spite of certain superficial resemblances, is definitely not a catalog from which such choices can be made, nor is it a cookbook for their application. It can help in constructing them, however.**

A silvicultural system also evolves over time as circumstances change and as knowledge of them improves (Marquis, Ernst, and Stout, 1992). A classic history of the management of red pine in Minnesota, by Eyre and Zehngraff (1948), exemplified this evolutionary process. The point of departure was the seed-tree system, which was found wanting because of the inadequacy of the seed supply. As markets improved, it became obvious that the shelterwood system had important advantages in enabling good regeneration, reducing invasion by shrubs, and allowing retention of the best trees for growth to optimum size and quality. In the years after 1948, intensive plantation silviculture became more common, but the evolution will probably not end.

Managing for Risk in Silvicultural Systems

As mentioned previously, an important component in designing a silvicultural system is understanding the unique biological, physical, social, and economic characteristics of the site and stand. A critical component of this is understanding the philosophical approach that should be made in regards to risk. It is not by chance that most native forests are now restricted to marginal lands and that their social and economic values are complex and multiple (e.g., water, recreation, biodiversity conservation, timber, climate mitigation). Taken singly, economic benefits from such forests are low, and comprise service values (water, carbon, recreation, conservation) that are difficult to capitalize. Conserving such forests is difficult because of this, and the silviculture for such management is complex, low intensity, and with low capital input using natural regeneration methods when and where necessary. Investment is in promoting nature's processes to achieve and realize economic benefits usually on long time horizons. Exposure to market fluctuations, diseases, and disturbances are therefore high and are mitigated by keeping financial and labor investments low, maintaining multiple species, and ensuring many social values, which taken together create a more resilient forest system (Puettmann, Coates, and Messier, 2008). Any one social or biological attribute may fail but the others will prevail. Species diversity and structural complexity are therefore important for both biological, social, and economic reasons (Box 6.1).

On lands where nature has provided much greater amounts of biological wealth, particularly where soils are deep, fertile, and moist, humans can afford to invest labor and capital to achieve a more rapid return in product or service value. The most extreme example of such an investment can be observed in intensive farming, where arable crops can be grown and harvested two to three times a year. People have learned to escape risk in market fluctuation and susceptibility to climate change, disease, and disturbance by shortening time of exposure. This can only happen on the best soils where time is on the forester's or farmer's side (see Box 6.1). If the crop fails, it is a failure in months. Reinvestment and a change in approach can start almost immediately. However, if this approach was taken when managing a forest on a rotation of 100 years with no alternatives other than a single invested crop, it would be catastrophic. This might seem obvious but the development of silvicultural systems incompatible with the risk for the site in question has been repeated time and again and always ends in failure.

Building a silvicultural system means that the forester needs to know both the social and biological context of a stand in relation to the degree of exposure to biological and social risk. The forester is therefore an investor and the forest and its composition is the stock portfolio. Under conditions of marginal returns (infertile soils, slow growth) investment should be in many species and markets – a diverse, risk-averse stock portfolio. When conditions can produce high returns over the short term, investments will tend to promote single species and single values – a simple but risk-prone stock portfolio.

Elements of Silvicultural Systems

Silvicultural systems are not chosen ready made from a manual, so it is logical to examine the various considerations that enter into their construction and evolutionary development (Florence, 1979). In the first place, a rational silvicultural system for a particular stand should fit logically into the overall management plan for the forest of which the stand is a part (Davis *et al*., 2001; Nyland, 2016). Second, it should represent the best possible amalgam of attempts to satisfy all of the following major objectives, each of which will be discussed here and in subsequent chapters. These basic objectives are as follows:

1) harmony with goals and characteristics of land ownership;
2) provision for regeneration;
3) efficient use of growing space and site productivity;
4) control of damaging agencies;
5) protection of soil and water resources;
6) provision for sustained yield of products and services;
7) optimum use of capital and growing stock;

Box 6.1 Understanding risk in silvicultural systems.

Silvicultural systems need to be appropriately applied to physical, biological, and socio-economic circumstance. Landscapes that are remote, infertile, steep-sloped, and erosion-prone will mandate systems that are non-intensive, working with natural regeneration on long cutting cycles or rotations, because of inherently low site productivity. On such sites, intensive site preparation and investment in a single crop is very risky because of very high capital investments and a long time horizon on returns. Income streams from single-species products on such sites will realistically be lower than on fertile sites. It is therefore best to secure multiple small income streams from many products and services that can be cultivated compatibly together and realized at different stages of stand development. Table 1 illustrates the differences in applying intensive (high capital, high silvicultural control, and high labor) versus non-intensive silvicultural systems (low capital, low silvicultural control, and low labor) for risk-averse and risk-reward circumstances. In soils with high fertility that are close to markets, crops can be grown fast with high yields. It makes sense to invest in intensive treatments and controls with this kind of return. Risk is avoided by the short return time and rewarded by the high yields and income. On more marginal lands, investments should be risk averse. Silvicultural systems can be designed as risk averse by considering resilience to both abiotic (e.g., wind, icestorms) and biotic factors (e.g., insects and disease). This can be done by including many species within each functional mode of regeneration (redundancy), and by including many different functional modes of regeneration (resilience) in order to create a multi-species, multi-regeneration-mode system. Designing silvicultural systems has a parallel to investing in the stock market: should a person or company invest in a single stock and thus take on more risk, or should the investment be in multiple stocks belonging to different risk categories.

Box 6.1 Table 1 Silvicultural strategies under risk-averse and risk-reward biophysical and socio-economic circumstances.

Strategy	Risk-averse circumstance	Risk-reward circumstance
Physical considerations		
Soil fertility	Low nutrients, drought prone, shallow and stony	High nutrients, ever moist, deep and well textured
Physiography	Steep sloped, exposed, unstable	Flat, sheltered, stable
Biological considerations		
Rotation	Long rotation	Short rotation
Regeneration	Natural regeneration methods	Artificial/planting
Age class	Multiple to all-aged	Single-aged
Species composition	Mixed-species	Single-species
Functional redundancy	High	Low
Resilience	High	Low
Socio-economic considerations		
Products	Multiple	Single
Use of labor	Low	High
Yields per crop	Low	High
Services	Multiple, high value	Single, low or high value
Income from products relative to services	Low	High

Source: Mark S. Ashton.

8) concentration and efficient arrangement of operations;
9) maintenance of desired plant and animal populations;
10) execution of policies about landscapes, scenery, and aesthetic considerations.

These objectives are as likely to conflict as they are to harmonize with one another. For this reason, the procedures followed in applying systems with the same name vary widely depending on the relative importance attached to different objectives. Some of the contradictions are partially resolved in the development of management plans for the whole forest. That process is essentially the same as what has come to be called ecosystem management (Christensen *et al.*, 1996).

The conflicting considerations can come in ways too numerous to mention except by examples. As will be pointed out later in this chapter, identification of the objectives of ownership usually simplifies the formulation by reducing the number of alternatives that might be considered. Unfortunately, both owners and regulatory entities sometimes have conflicting or excessively demanding objectives.

The requirements for regeneration are discussed at length in many other chapters. These requirements are so crucial that the naming of systems for regeneration methods is a custom designed to remind foresters that some other objectives must be sacrificed to the need for timely regeneration. Continuity for any forest landowner values, even the maintenance of old-growth stands and old reserves with trees thousands of years old, ultimately and absolutely depends on replacing old trees and stands with new ones.

Efficient use of growing space depends on more than securing prompt uniformly distributed regeneration. Consideration must also be given to subsequent measures to deal with deficient or excessive stocking by thinning and other techniques. Provisions may have to be anticipated to exclude desirable plants or control them if they appear. Efficient use of site productivity usually requires planning for the termination of rotations when trees become mature and growth declines. The growing space can be depended upon to fill with vegetation. Silvicultural systems are, among other things, programs for determining what fills growing space and for how long.

Examples of Application in Silvicultural Systems

It is inevitable that stands of trees will suffer some damage during their rotation periods. Some of it can be forestalled by building stands that are more resilient to damage. In many cases it is unwise to grow certain kinds of stands because they may, for example, produce too much fuel, making them susceptible to fire or defoliating insects. However, there are silvicultural techniques for making otherwise susceptible stands less susceptible to these risks (see Chapter 26).

Forest ecosystems are not just trees, they always encompass animals and non-woody plants in addition to trees. In fact, sometimes the non-tree organisms, wild or domestic, are more important to owners and society than the trees. Even if the ownership does not want them, they must be considered in forest management either because they can become pests or weeds, or because under most legal systems, the public has a protective and regulatory interest in them. Animals are governed mainly by plants and silviculture is a means of governing plants. Applying the principles of silviculture to produce the desired kinds of habitats is therefore critical (see Chapter 24).

Most silvicultural treatments of forest vegetation do not greatly affect soil and water detrimentally. In fact, treatments of watersheds to increase the resilience of the forest for long-term yield and quality of drinking water is an important objective of many municipalities that own forests (see Chapter 29). However, any disturbance of soil associated with treatments may harm soil and water resources. For example, the spatial patterns of cutting that are controlled by silvicultural systems may determine the extent and location of the roads and trails that inevitably damage soil and may cause erosion and stream sedimentation (see Chapter 23).

Silvicultural provisions for sustained yield of benefits from forests are usually thought of in connection with wood supply and will be dealt with in more detail in timber management (see Chapter 30). However, the same balanced distribution of age classes needed for sustained yield of timber also makes a major contribution to sustaining the diversity of habitats that is the foundation of biodiversity. Because it is seldom feasible to obtain sustained yield from individual stands, it is sought from combinations of stands. Sustained yield is a goal that can be approached through decades of deliberate effort but is seldom perfectly achieved. Therefore, each silvicultural system should be designed with the understanding of the degree to which ownership will support efforts at achieving the goal.

Just as the medical profession is committed to curing patients, so is the forestry profession committed to keeping forests healthy and productive forever. However, both professions must deal with patients who will not or cannot invest in preventive and curative measures. In the case of forests and forest owners, the stumbling block is resistance to making long-term capital investments. Even the act of leaving saleable trees standing in the woods for additional growth is a kind of investment in growing stock. Planting trees can be one of the most far-seeing investments that people make. Thinning and many other details of silvicultural systems are designed to bring forest owners adequate returns on their investments. The degree to which sustained yield can be achieved often depends on how successful these measures are. Since most monetary returns to owners from silviculture come from timber management, these measures are also dealt with in Chapters 22 and 30.

Forests and all their plants are part of the landscape and scenery for which the public is asserting a growing interest. An increasingly urbanized population regards the ugly appearance of cuttings as clear evidence of forest devastation and is pressing for arbitrary regulations about silvicultural practices. This calls for measures to screen or mitigate whatever is deemed unsightly, whether

or not they relate in any way to the ecological integrity of the stand. Silvicultural treatments can be arranged in ways that expose attractive features or distant vistas to public view along roads or trails. In addition, the edges of cutting areas should be manipulated so that they do not look artificial from a distance. It is usually easier to do partial cutting along roadsides than to explain that a clearcutting and planting operation is environmentally benign and will ultimately produce a beautiful stand (Jones, 1993; Crowe, 1978; Bacon and Twombly, 1980) (see Chapters 23 and 32).

All these different considerations represent forces that pull foresters and forest owners in many directions. Analysis will show that single-minded concentration on any one of these objectives can ultimately lead to undesirable results. The best solutions lie in finding the most appropriate blends of all significant objectives. Fortunately, the various considerations do not always conflict, and often the goals are complementary.

Role of Ownership Objectives in Formulating Silvicultural Systems

Decisions about the design of silvicultural systems are greatly simplified by clarifying the objectives of ownership, whether it be public or private. This logical first step automatically eliminates many of the possible alternatives. It also forces recognition of the fact that it would not necessarily be in the interest of two different owners to manage the same stand in the same way. Except to the extent that law may dictate certain actions, there is no justification for a forester to embark in arrogant wisdom on any "standard" procedure for the growing of a particular kind of stand, regardless of whether the technique fits the owner's purposes.

Foresters must often help owners select their own objectives before formulating a silvicultural program. This is partly because owners may not have a clear idea of what objectives are reasonably attainable. The objectives of ownership clearly dictate the relative amounts of attention that is to be paid to management for timber, wildlife, forage, water, recreation, scenery, or other potential benefits of forests. The objectives of ownership are always modified by various public laws and regulations that reflect the objectives of society.

On land managed for multiple use (Burns, 1989), the silviculture logically differs from that on similar land that might be owned by a lumber company primarily for growing sawtimber. This would in turn differ from a paper company's silviculture for pulpwood production. If an owner is most interested in wildlife or in preserving some old growth for aesthetic purposes, the forester should modify the silviculture accordingly. In fact, the forester's occupational bias in favor of efficient timber production can sometimes be more of a liability than an asset. But this is changing, as the profession recognizes the enormous range of social and other non-timber values that landowners and the public desire. Timber is now a secondary benefit for most of America's public forests.

Analysis of the objectives of ownership will normally define the kind of vegetation to be maintained, the kind of trees that are to be grown, and the amount of time, money, and care that can be devoted to the process. The intensity of practice is determined by the nature of the site and the amount of money that the owner is willing and able to place in long-term silvicultural investments as well as by the financial return required on such investments. If long-term investments cannot be made, the silvicultural treatment may be limited to what can be done in the process of harvesting merchantable timber. Where the future of the enterprise seems limited to the life expectancy of the owner, attention may be restricted to securing maximum benefits during the owner's prospective lifetime; manipulating the existing growing stock would probably take precedence over securing regeneration. If the owner's objectives do not include production of timber or profits, the forester should manage stands accordingly.

Resolution of Conflicting Objectives

There is no inherent harmony among the various major objectives sought in managing stands and forests. Maximizing several major objectives at the same time together is usually impossible. Harmony can be created only by weighing the various objectives individually and inventing silvicultural systems that represent a compromise. Planning for forest or ecosystem management is created by the same kind of procedure but at much larger scales (Forest Ecosystem Management Assessment Team, 1993). The tension is most evident if all forestry is considered in general. Fortunately, the conflicting objectives need be resolved only for particular forests or stands. Analysis of each situation will usually reveal a few limitations; the necessity of giving first attention to these will simplify and govern solutions.

Sometimes when two or more problems arise, each of which is separately unsolvable, with careful silvicultural design they can be combined into a complementary single solution. The process starts with a consideration of the goals of the forest owner. Each of the remaining objectives must then receive some attention. It would almost invariably be a mistake to pursue any single one to the bitter end. The analytical process generally works downward from the forest to the stand, but not without the formation of some preliminary idea of the range of treatments and results that are silviculturally feasible. Some absolutely restrictive natural factors are bound to

exist, and these must be recognized early in the process. However, the remaining latitude of silvicultural possibilities is generally broad enough that further efforts to develop some optimum silvicultural system is normally based on analysis of the effect of all factors, natural and social.

Silviculture by Stand Prescription

Silvicultural treatments are best prescribed, stand by stand, by foresters on the ground. However, the general forms of silvicultural systems that may be prescribed and the basic management policies ordinarily have to be determined for the forest ownership as a whole. Some degree of standardization is necessary to ensure uniformity and continuity of action. Too much standardization can lead to treatments that fit well in some stands but badly in others. Results can become especially poor if conformity to standard operating procedures causes or allows field personnel to stop thinking about silvicultural problems.

The need for quasi-independent stand prescription is illustrated by the fact that it may be logical to clearcut and replace an unhealthy 35-year-old pine stand and yet thin a healthy one, even though both are located side by side on the same site within the same ownership. A standard procedure for all 35-year-old pine stands would dictate that the two be treated the same. Most decisions like this are more sophisticated and complex than in this simple case, but the principle is the same.

Foresters on the ground should be able to detect matters of silvicultural significance that are not obvious to others viewing stands from roadsides, distant offices, or legislative chambers. Policies about the objectives of forest management are determined by forest owners, public or private, under the constraints of laws and regulations. The role of professional foresters is to help develop such policies and to execute them through the formulation and prescription of silvicultural treatments and systems. In some places laws require that these functions be carried out only by licensed professional foresters, usually to protect various public interests. However, this is not always the case. Forest policies are often poorly conceived and badly executed. It is the traditional responsibility of the forestry profession to correct such situations both as a matter of principle and as a way to avoid being blamed for them.

Few forms of human endeavor have more distant time horizons than those of foresters. Foresters must try to predict the nature of the future forest and explain this to those who govern forest policy. Silvicultural systems are the programs designed for reaching the policy goals. The time periods involved, usually one or more whole rotations, are long enough that the goals and the means of achieving them usually change before they are reached. On occasion the programs must be modified and kept flexible so this can happen. Such changes of method in time and within stands are likely to be common when a forest is, like most American forests, being brought under management for the first time or lands are under new ownership. In fact, it is rare that forests and the stands within them will follow any one directive over the course of their growth because landownership and public values change more quickly than almost all forests and trees grow. However, it is by these changes that the procedures are perfected and the pattern of stands is continually molded into arrangements that are rational from the standpoint of site variations and management objectives.

Classification of Natural Regeneration Methods

The main purpose of the terminology of the methods is to indicate the focus of regeneration origin and the effect that the spatial arrangement and timing of final harvest cuttings has on the sizes, shapes, and arrangements of new stands. These matters are so important for the administration, harvesting, use, and protection of forests that the name of the regeneration method is often applied to the whole silvicultural system by which a stand is managed. The patterns of stand structure exist in terms of acres, but the factors that control the establishment of new plants, as presented in previous chapters, depend on what happens or is done on **square yards or inches** (meters or centimeters) (see Chapter 5). The term *regeneration method* is mostly a device to carry information about silviculture into overall forest management planning.

The simplest historical classification of regeneration methods is based on (1) the spatial arrangement of cuttings and age classes and (2) the distinction between seedlings and sprouts as sources of regeneration. The one most widely accepted in North America includes **seed/seedling-origin methods** (**high forest**) and **vegetative-origin methods** (**low forest**). As with many classifications, there is a wide range of variation in each category and some borderline cases may not clearly fit any pigeonhole. The methods are described below.

Seed/seedling-origin methods: production of stands originating mainly from seed and that can be considered to produce a tall-statured forest or woodland over a longer period of time relative to a forest of the same species but of sprout or vegetative origin managed on shorter rotations (low forest). Clearcut, seed tree, shelterwood, and selection are generally considered to create high forests. However, there is nothing to suggest that forests of sprout origin cannot attain high stature if managed on long rotations.

1) **Clearcutting method**: removal of the entire stand in one cutting with reproduction from seeds germinating *after* the clearing operation either coming from outside the stand (e.g., disseminated by wind, small birds, bats) or *in situ* (e.g., buried seed bank, serotiny). Groundstory site treatments associated with clearcuts are usually lethal (e.g., fire, scarification).
2) **Seed-tree method**: removal of the current stand in one cutting, except for a small number of seed trees left singly or in small groups. The environmental conditions are similar to those of a clearcut and therefore do not exclude species that regenerate well in clearcuts. However, the focus of the method is on including heavy-seeded species with poor dispersal but that also require open conditions. Many of the target species could be considered long-lived pioneers. Groundstory site treatments are similar to those done in clearcuts.
3) **Shelterwood method**: removal of the current stand in a series of cuttings, which extend over a relatively short portion of the rotation. This is done by first establishing one cohort of advance reproduction under the partial shelter of seed trees. In this regeneration method, a nearby source of both seed and shade is desired to accommodate species that are shade tolerant and to moderate the colonization of shade-intolerant pioneer species. Groundstory treatments are usually more moderated and intended to protect or establish and then release existing vegetation before final canopy removal. Depending upon the degree of shade and groundstory, occupancy of advance reproduction does not preclude the establishment of regeneration targeted in the clearcut and seed-tree methods or regeneration of vegetative origin.
4) **Selection method**: continual creation or maintenance of an uneven-aged stand that meets the definition of all-aged. This is done by the periodic replacement of single trees, small groups, or patches of trees with regeneration from any source primarily being defined by opening size and site treatment within opening. Shade-intolerant pioneer species will primarily dominate patch-sized openings with lethal site treatments while shade-tolerant species reliant upon advance reproduction will dominate single-group to small-group openings with no site treatments.

Vegetative methods: production of stands originating almost entirely from vegetative origin and that can be considered to produce a short-statured forest or woodland over a shorter period of time relative to a forest of the same species but of seedling origin. Coppice is generally considered to create low forest if managed on short rotations.

1) **Coppice methods**: production of stands originating primarily from vegetative regeneration. Given the intensity of the cutting and the vigor of sprouting it is unusual to find regeneration of any other mode of origin (e.g., buried seed bank, advance regeneration, newly germinated seedling).
   a) Coppice method – any type of cutting in which dependence is placed mainly on vegetative reproduction.
   b) Coppice-with-standards method – the combination, on the same area, of short-rotation coppice growth with scattered trees, which are grown on longer rotations and may be of seedling origin.

Each one of these methods has many modifications, and foresters will devise more. There are also combinations of methods that mainly relate to the nature and pattern of structures and age classes left behind. The more detailed classifications that exist do not differ in basic principle from this simplified classification. Some of the most sophisticated schemes are found in the German literature (Dengler, 1990; Burschel and Huss, 1987; Mayer, 1977). In the English literature, many silvicultural systems are described and classified, as applied in many parts of the world (Matthews, 1989).

Paradoxically, the various methods of regeneration do not control the regeneration process as much as the words imply. The actual processes and treatments that cause forest regeneration were discussed in several previous chapters. However, names of the regeneration methods do convey some information about whether the regeneration comes from seedlings that originated from seed after the cutting, advance regeneration that established before the removal of the canopy, or vegetative sprouts. Selection is the only method defined by having many age classes (meaning four or more). Seed-tree, shelterwoods, and coppice systems can have two to three additional age classes (making them multi-aged) but they have one primary regenerating age class. Clearcuts are defined by almost always one age class.

The terminology of regeneration methods tells only a little about the details of the silvicultural systems by which the dynamic, rotation-long developmental processes of stands are guided. A silvicultural system partly guides and is partly driven by one of the stand development processes described in Chapter 4. However, the name of the regeneration method describes enough that it provides a good starting point.

The Basis of Distinction Between Methods of Natural Regeneration

The first distinction can be made between methods involving regeneration from seed, and methods that rely mostly on vegetative regeneration from stump sprouts, root suckers, lignotubers, or layered branches.

Regeneration by planting is usually categorized as being part of the seed/seedling-origin method, as does that from the release of advance growth and the resprouting of small advance growth (e.g., seedling sprouts).

Coppice methods of regeneration are often called "low-forest" methods because they are thought of as being limited to growing short trees on short rotations for fuelwood. Because tall, old trees of many species, including mighty oaks and coast redwoods, can be grown from sprouts, "low" should not be interpreted literally. Coppice regeneration methods given long rotations and the right choice of species lead to high forests. However, most coppice regeneration methods still predominantly lead to low forests because the products produced are based on metrics of gross biomass (fiber, fodder, fuelwood) rather than dimension (timber). The coppice regeneration methods may include some regeneration from seed, and many broadleaved high forests of shelterwood origin, have some important sprout regeneration.

With regard to the arrangement of all forest cutting methods in a timeframe, the most important distinction is between (1) methods for the maintenance of even-aged or single-cohort stands in which regeneration cuttings are concentrated at the end of each rotation, and (2) methods in which regeneration cuttings extend throughout the rotation leading to the creation of balanced uneven-aged or all-aged stands.

The complexity of many classifications results from recognition of the almost infinite variations that can be created in the horizontal, geometric pattern of cutting areas. Each general method can be applied so that openings and the uncut trees are left either in uniform distribution or in concentrated strips, groups, wedges, or other variations. In the general classification used here, simplicity has been achieved largely by restricting the amount of attention given to differences in spatial arrangement within stands.

The clearcutting methods create highly uniform stands that can extend over substantial areas (Fig. 6.1). The seed-tree methods produce essentially the same result but with a few reserved trees as a seed source within the stand (Fig. 6.2). Reliance on advance regeneration established in reduced light under older stands that are removed in stages is characteristic of the shelterwood methods. The new stands are usually even-aged or of single cohorts, but there are many examples of residual groups or individuals that are left to create additional two to three age classes (multi-aged). These methods would be considered uneven-aged but usually unbalanced (Fig. 6.3). Selection methods produce uneven-aged stands that are all-aged (Fig. 6.4) with at least four age classes that are usually balanced. Coppice methods usually produce uniform even-aged or single-cohort stands, although they can be comprised of different age classes (Fig. 6.5). The coppice-with-standards methods usually maintain sparsely stocked older trees of one or more age classes above uniform stands of low trees of sprout origin.

The method of regeneration being employed in a given stand may not be evident to the casual observer.

Figure 6.1 Young seedlings of Scots pine establishing after a clearcut, Finland. *Source:* Mark S. Ashton.

Figure 6.2 A single-aged (single-cohort) stand of ponderosa pine, western larch, and other conifers in Flathead National Forest, Montana, after a seed-tree cutting that will lead to the establishment of a second cohort composed of the same species. *Source:* US Forest Service.

Figure 6.3 The establishment of a single-aged (single-cohort) stand of western white pine, sugar pine, white fir, and ponderosa pine beneath the first cutting (preparatory cut) of a shelterwood in the Sierra Nevada mixed conifer forest, California. *Source:* Mark S. Ashton.

Figure 6.4 An uneven-aged stand managed as mixed species and all-aged through single-tree selection of Norway spruce, European beech, and silver fir in a farmer's woodlot, Bavaria, Germany. *Source:* Mark S. Ashton.

Figure 6.5 A simple coppice of European chestnut in southeast England, UK. *Source:* Mark S. Ashton.

The identification and definition of a method of cutting depends as much on the results actually obtained, the intent of the treatment, and the nature of subsequent operations, as they do on the pattern according to which the trees are removed. A regeneration cutting is a regeneration cutting only to the extent that it leads to the initiation of new trees. If something intended as a thinning results in the establishment of vigorous reproduction, it is best regarded as having been the start of a shelterwood cutting. However, if the residual stand is then allowed to suppress the reproduction to the point of elimination, the initial cutting was indeed a thinning.

A partial cutting aimed at starting the development of an uneven-aged stand is a selection cutting only if subsequent operations are sufficiently consistent with the first, leading to many age classes.

Classification of Plantations and Artificial Seeding

The classification of plantations can be defined by age class, mixed-species, or single-species composition, and arrangement both in space and over time (Savill, 1991; Evans, 1992). Like natural regeneration methods, plantation systems can be divided by forest stature as high and low forest, again largely based on seed or vegetative origin of planting.

High-forest plantations can be defined as those plantings of seedlings, rooted cuttings, or artificial seedings that give rise to tall-statured forests managed over relatively long rotations or cycles relative to low-forest plantations.

1) **Single-species single-aged plantations:** shade-intolerant seedling stock usually categorized as pioneers that are planted together at a fixed spacing. Species are capable of establishing in open and often desiccating conditions and grow well together (Fig. 6.6a).
2) **Mixed-species single-aged plantations:** seedling stock of mixed composition that are compatible in shade-tolerance and intimate growth and that are planted together at a fixed or variable spacing at one time (Fig. 6.6b).
3) **Mixed-species two- or three-aged (multi-aged), or all-aged plantations:** seedling stock of mixed composition that are compatible in shade tolerance and intimate growth and that are of two or three or more age classes, planted at fixed or variable spacing (Fig. 6.6c).

Low-forest plantations can usually be defined as those plantings of vegetative origin (e.g., cuttings) that give rise to short-statured multi-sprouting forests managed over very short rotations, and after planting, often are dependent upon the coppice natural regeneration method for continued regrowth that eventually leads to replacement with new plantings.

1) **Single-species single-aged cuttings:** shade-intolerant vegetative stock usually planted at close spacing for biomass, fiber, fruit, nut, or leaf production. Species selected were often originally understory shrubs of natural forests (tea, coffee) or pioneers with sprouting ability (acacia, albizia, cottonwood, willow).
2) **Mixed-species single-aged cuttings with standards:** shade-intolerant vegetative stock interplanted with standards of seedling or vegetative origin at a wider spacing and that chiefly serve as shade trees (Fig. 6.6d).

(a)

Figure 6.6 **(a)** An 8-month-old irrigated and fertilized single-species single-aged planting of teak (*Tectona grandis*) on old fields in Honduras. *Source:* A. Finkral. Reproduced with permission from A. Finkral.

(*Continued*)

Figure 6.6 (Continued) **(b)** A 1-year-old mixed-species single-aged (single-cohort) plantation of *Gliricidia sepium* (vegetative sticks), *Michelia champaca*, and *Swietenia macrophylla* (mahogany) in the central highlands, Sri Lanka. **(c)** Mixed-species two-aged plantation comprising an overstory of Caribbean pine and newly planted seedlings of dipterocarps (luan, meranti) in southwestern Sri Lanka. **(d)** Mixed-species single-aged (single-cohort) stand of vegetative cuttings with standards – established tea cuttings with a spaced overstory of clove trees (*Syzygium aromatica*) and *Gliricidia sepium* in the central highlands, Sri Lanka. *Source:* **(b–d)** Mark S. Ashton.

The Basis of Distinction Between Methods of Planting

Most of the world's plantation timber trees, those species that make up 90% of timber plantations worldwide, comprise no more than 20 species (Savill, 1991; Evans, 1992). All would be considered to grow well in single-species, single-aged plantations. This is because all would be considered fast-growing shade-intolerant species that in nature would be considered to belong to the functional group, "pioneers of stem exclusion." They compete well against weedy vegetation, grow densely together with efficient leaf area to sapwood area ratios, and with columnar, compact leafy crowns and monodominant stems. North American examples are cottonwood, sweetgum, loblolly pine, slash pine, and Douglas-fir.

High-Forest Plantations

Cultivating mixed-species single-aged plantations is critical if the focus is to establish later successional shade-tolerant species that perform poorly in open desiccating conditions. Under these circumstances, creating a partial shade environment for their establishment and

growth is critical. This can be done by interplanting faster-growing shade-intolerant species of either or both functional groups categorized as "pioneers of stand initiation" or "pioneers of stem exclusion" (see Chapter 5). The same approach can be used to cultivate species prone to density-dependent effects of insects and disease. Beneficial growth can be obtained when unrelated taxa are planted together, especially in tropical, ever-wet, and humid conditions, where diseases and insects are ever present and species specific (Champion and Seth, 1968; Evans, 1992). Finally, mixtures can provide facilitative growth interactions especially between nitrogen-fixing tree species and non-nitrogen-fixing tree species.

Most mixtures can be planted as single-aged stands following initial floristics models (Oliver and Larson, 1996). However, mixtures can also be planted sequentially as mixed-species, two-aged or multiple-aged plantations. Usually the pioneer species is first planted to ameliorate the site. This is followed by planting late-successional species. Under this scenario the model would be following relay floristics (Oliver and Larson, 1996). Such circumstances are most appropriate under conditions that are so abnormal that the site needs considerable mitigation by pioneer species that increase shade and soil fertility to facilitate the establishment of others. This usually fits conditions of strong degradation such as mine spoils or severe types of soil erosion.

Low-Forest Plantations

Low-forest plantations are almost always entirely vegetative in origin. Single-species single-aged cuttings are usually planted at high densities to achieve high biomass. Many cuttings are clonal, meaning that the stock is all genetically the same across the planting. Such systems are designed to produce very uniform amounts of fiber and biomass (cottonwood) or leaves (tea, yerbe mate) on short rotations. Mixed plantings are used to facilitate increases in quality or yields of clonal products. This is usually done by interplanting "pioneers of initiation" (many are nitrogen-fixing) to increase shading and soil fertility for clonal plantings beneath that comprise the low-statured clonal cuttings of shrubs such as tea, coffee, and cinnamon.

Naming Silvicultural Systems: The Taxonomy

Treatments are first devised to fit the circumstances and the naming of them is done afterward. In other words, the terminology describes the treatment but does not dictate it. It is descriptive rather than prescriptive. The long-standing terminology of regeneration methods should be used to the extent of its capacity for providing information in meaningful terms to foresters. However, this should be supplemented with adjectives that convey the additional, detailed information that is usually necessary. Methods of regeneration, the site treatments, and the kinds of stand structures left or removed, are all classified and recognized largely because the act of doing this indirectly forces managers to plan for the future care, development, and replacement of stands. It also facilitates the proper communication of your intent to others.

Sloppy use of the terminology can corrupt it to the point where the words mean little. *Selective cutting* is a potentially useful term that slovenly usage has almost destroyed as a technical term. It seldom helps to try to redefine existing technical or common terms. *Clearcutting* is really a word with many meanings as well as an ugly connotation. As a term of technical silviculture, it is an attempt at defining a particular environmental condition, meaning lethal both to the above- and below-ground vegetation, where all growing space is made available for almost immediate colonization by seed from outside or within the soil afterwards. However, foresters, policy makers, and the lay public liberally use the term to mean almost any forest cutting.

The best and most methodical way of thinking about naming a silvicultural system is to first start with a focus on the age class (see Box 6.2; for use of nomenclature, see Glossary of Terms, or Chapters 3 and 4). For example in methods of natural regeneration, if the objective is to maintain or create an uneven-aged stand that is all-aged (four age classes or more) without one age class clearly dominating growing space, then the identifying characteristic is "selection." If the objective is to maintain or create a stand with one age class dominating growing space, then the system would be defined as "even-aged" or "single-aged" and categorized into either true clearcut, seed tree, shelterwood, or coppice. If the objective is to create or maintain an uneven-aged stand that is multi-aged (two or three age classes) then the terms "irregular" and "reserves" would be used to define seed tree and shelterwoods, or a coppice with standards. In general, age classes are usually unbalanced with one dominating age class, being the most recent regenerating one.

The second identifying characteristic is origin of regeneration that is being fostered. For single-aged stands of clearcut origin, regeneration would exclusively include true pioneer seedlings that arose from seed outside the stand or from the seedbank. For single-aged or multi-aged stands of seed-tree origin, regeneration would include the same component of pioneers as clearcuts but would also include heavy-seeded pioneers that have poor dispersal. For even-aged or multi-aged stands of coppice origin, regeneration would be either purely vegetative or with a small component of seedling origin. Stands of shelterwood origin include regeneration which is the most inclusive, including regeneration of clearcut, seed tree, and

Natural regeneration systems

1. Is the stand balanced and all-aged with no dominating age class?
   Yes: **Selection system** No: **Proceed to another question**

Is the nature of the harvest removing single canopy trees uniformly across the area?
Yes: Single tree selection
No:
a. Removing single strips of trees repeated at intervals across the stand: **Strip selection**:
b. Removing groups of canopy trees (approximately 3–10 individuals together) across the stand: **Group selection**
c. Removing patches of trees (approximately 0.5–2 acres/0.2–1 ha in size) across the stand: **Patch selection**

2. Is the stand defined predominantly or entirely by vegetative regeneration?
   Yes: **Coppice system** No: **Proceed to another question**

Is the stand single-aged or of a single cohort?
Yes:
a. The stand is uniformly closed-canopied across a patch-shaped stand: **Simple coppice**
b. The stand is single-aged or of a single cohort within a hedgerow or corridor: **Line coppice**
c. The stand comprises sparsely spaced trees with vegetative sprouts that originate at 3–6 ft (1–2 m) height above from the severed bole of trees: **Wood pasture**

No:
Does the stand have larger individual trees of seedling origin within the stand?
Yes:
a. The stand has uniformly distributed larger seedling origin trees within a patch-shaped stand: **Coppice with standards**
b. The stand has larger seedling origin trees within a hedgerow or corridor-shaped stand: **Line coppice with standards**
c. The stand has larger seedling origin trees within a wood pasture: **Wood pasture with standards**

3. Is the stand defined by a single age class of small-seeded well-dispersed (water/wind/fire/small bird) or buried seed bank vegetation that is shade intolerant?
   Yes: **Clearcut system** No: **Proceed to another question**

Does the stand have any residual snags or a few widely spaced immature live trees?
Yes: **True clearcut with reserves (irregular)**
No: **True clearcut**

4. Is the young stand defined by a mix of vegetation of the sort described in a true clearcut but with additional shade-intolerant species that are heavy seeded and poorly dispersed?
   Yes: **Seed tree system** No: **Proceed to another question**

Are there other older age classes or cohorts of trees left after removal of seed trees?
Yes: **Seed tree with reserves (irregular)**
a. Individual trees arranged in groups: **Seed tree with group reserves**
b. Individual trees arranged singly: **Seed tree with single tree reserves**
No: **Seed tree**
a. Seed trees arranged singly: **Uniform seed tree**
b. Seed trees arranged in groups or strips: **Group or strip seed tree**

Figure 6.7 An example of a decision model depicting a logical and descriptive way of naming silvicultural systems for natural regeneration methods: five questions to consider. *Source:* Mark S. Ashton.

5. Is the stand defined by the presence of advance regeneration (other modes of regeneration may be abundant, infrequent or may not be present) of shade-intermediate to shade-tolerant tree species that are heavy seeded and poorly dispersed and/or require shade for germination?
   Yes: **Shelterwood**

↓

Was the advance regeneration present before the harvest and the removal of the canopy made entirely in one cutting?
Yes: **One-cut shelterwood**
No: Are there other older age classes or cohorts of trees left after removal of parent shade/seed trees?

Yes: **Shelterwood with reserves (irregular)**

- **a.** Individual trees arranged in groups or strips: **Shelterwood with group or strip reserves**
- b. Individual trees arranged singly: **Shelterwood with single tree reserves**
- c. Trees arranged variably around expanding gaps with 3–4 age classes (cohorts): **Group shelterwood with reserves (femelshlag)**

No: **Shelterwood**

- a. Individual parent trees arranged singly and then removed: **Uniform shelterwood**
- b. Individual parent trees arranged in progressive strips which are all eventually removed: **Strip shelterwood**
- c. Individual trees taken out together as groups to form openings that are progressively expanded and then finally removed: **Group shelterwood**

Figure 6.7 (Continued)

coppice, in proportions dependent upon the site treatments and degree of shade. However, the most important indicator of a shelterwood is the presence of regenerating species that rely upon advance reproduction. Selection systems should not be defined by the nature of their regeneration but by their many age classes with no particular age class strongly dominating the stand. Opening size and site treatment can define origin of regeneration for selection as much as any of the even-aged or multi-aged systems (Fig. 6.7, Box 6.2; for use of nomenclature see Glossary of Terms).

After defining the age class and regeneration origin of a silvicultural system, other descriptors relate to: (1) the pattern and nature of the operation (e.g., uniform, strip, group, alternate, line), and (2) structures that are left behind (e.g., reserves, standards, snags, legacy trees). Adding descriptors to the name of a silvicultural system that reflects pattern of operation and the structure and composition that is retained post regeneration can be very useful for understanding the complete intentions of the forester and landowner management objectives.

The Silvicultural System as a Working Hypothesis

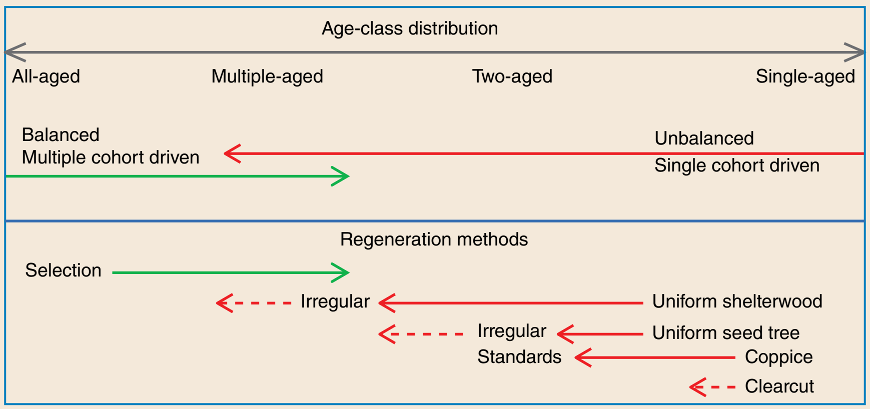
The practice of silviculture must be conducted in the absence of complete knowledge about natural and changing social factors that affect each stand. Furthermore, most of the treatments cannot be properly evaluated until many years after their application when the results become more evident. Decisive action cannot await absolute proof of validity, nor can it be evaded indefinitely by fence straddling. Thus, the forester must proceed as far as possible on the basis of proven fact and then complete plans for action in light of the most objectively analytical opinions that can be formed. This combining of fact with opinion is treacherous, especially because people easily become committed to opinions when they base actions on them. Such opinions can then be mistaken for facts.

The soundest basis for action derived from a mixture of proven fact and unproven opinion is the **working hypothesis**, which is the best estimate of truth formed by analyzing all available information. It is not allowed to become a ruling doctrine but is, instead, constantly tested against new information and modified accordingly. It should not be embraced so wholeheartedly that it cannot be discarded and replaced. A forester must always be ready to admit, at least inwardly, that an earlier decision was wrong and correct the procedures accordingly. It is important to monitor the results as objectively as possible, as described for **adaptive management** earlier in the book (see Chapter 1)

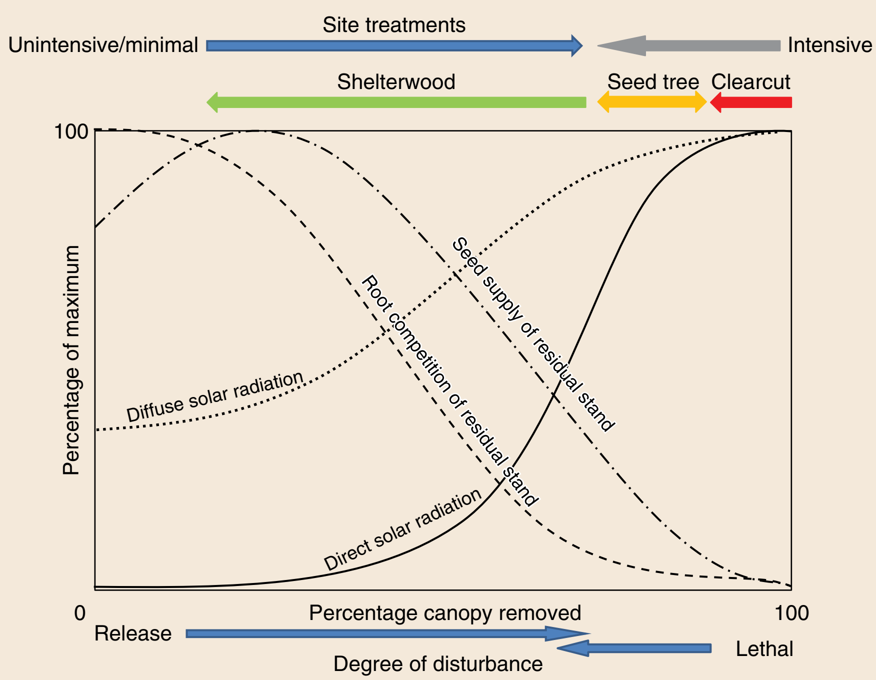
The silvicultural system is logically based on a working hypothesis and is altered through adaptive management as it becomes necessary to change the hypothesis. If a silvicultural system does become ruling doctrine, existing procedures should be constantly examined to determine whether it has outlived its time or has become inconsistent with new information. For example, it is logical to consider whether silvicultural practices developed for manual logging remain valid under mechanization.

Box 6.2 Defining the conceptual differences among natural regeneration methods.

Differences among natural regeneration methods can be graphically represented. Clearcut, seed-tree, and shelterwood systems start with the premise that their simple applications end up producing single-aged (single-cohort) stands (even-aged systems). However, other age classes (cohorts) can be left behind in various arrangements and structures (called reserves) after successful regeneration of the youngest age class (cohort) as long as the older overstory does not impede the development of the regeneration (unbalanced multi-aged systems) (see Fig. 1). All of these variations with two to three age classes (cohorts) are defined as irregular. The regeneration methods most dependent upon the more lethal site treatments to secure the more shade-intolerant regeneration retain the simplest and most open arrangements of reserves. Shelterwoods can retain the most complex and most closed arrangements of reserves given the focus on securing advance regeneration, some of which can be very shade tolerant (see Fig. 2).



Box 6.2 Figure 1 A depiction of age-class distributions and the nature of how regeneration methods approach reflecting them either as unbalanced (even-aged systems) or balanced (selection systems). *Source:* Mark S. Ashton.



Box 6.2 Figure 2 A conceptual depiction of the different approaches to regenerating stands using even-aged approaches. *Source:* Mark S. Ashton.

Similarly, it is good to question whether thinning policies should not be altered when it is found that the rate of diameter growth does not, as was once believed, control the properties of wood. It may be necessary to initiate prescribed burning if previous policies of fire exclusion have caused dangerous accumulations of forest fuels. Most good ideas survive to be overdone, so they should continually be evaluated and modified as necessary.

Radical changes and excessive fluctuations in silvicultural procedures lead to confusion and lost motion. If the

Figure 6.8 One-and-a-half centuries of evolution in silvicultural practice in Bavaria illustrated in three stands at the Forest of the Technical University of Munich. The Scots pine stand in the background was established by direct seeding 150 years ago on soils degraded by long periods of overuse. On the left is a Norway spruce plantation established 70 years ago where the initial pines had been harvested and the soil had improved enough to allow the spruces to grow. On the right is a planted stand of mixed hardwoods, 30 years old, which represents the re-establishment of a forest resembling the original one hundreds of years ago and believed to be resistant to many of the maladies that pure spruce plantations sometimes suffer. *Source:* Yale School of Forestry and Environmental Studies.

silvicultural system for dealing with a particular local kind of stand has been kept in conformity to circumstances by occasional modifications, disruptive reforms are unlikely to be necessary. It is also prudent to avoid the temptation to discard tested procedures in favor of radically different untested ideas because of problems of the moment. If once promising plantations become riddled with root rot, one should not necessarily swear off planting. Neither should the lapse of 9 years between good seed crops cause a wholesale shift to artificial regeneration.

Forestry is special to the extent which the actions of the present govern those of future generations of practitioners. Any treatment that is applied to a stand now is likely to restrict the choices available in subsequent treatment. In a sense, the forester conducting a treatment in a stand is entering into a pact of mutual understanding with succeeding foresters about the stand. Current foresters should expect that the plans put into effect now will be given the benefit of the doubt by their successors, but not to the extent of unquestioning adherence.

The results of treatment that are most difficult to change are species composition and age-class structure of stands, so changes in these attributes should be approached with deliberation. It must be be recognized that the period of regeneration is for all intents and purposes the only one during which major changes can be made in stand characteristics and silvicultural systems. The period of intermediate cutting is more one of modification than of change. Many stands are inherited from the past, and those that are new provide the best opportunity to create new structures and species combinations for the future (Fig. 6.8).

Summary Remarks

The silvicultural system should be built where it is to be used, not prefabricated and brought from some other kind of forest. Furthermore, silviculture has too often been conducted based on the view that each method or system constitutes a rigid set of procedures, usually defined in quantitative terms, which, if it is religiously followed, will produce optimum results. There has even been the view that all silvicultural practice in a given locality should follow a single method or system. These rigid views have too often resulted in natural, economic, or political disaster.

No one method or system has any single ideal routine of application akin to the precise movements of parade-ground drill. There is, for example, no one kind of shelterwood system compared with which all others

are inept or imperfect imitations. If they have these attributes, it is not because of departure from some preordained ideal treatment program. None of these methods is a schedule or routine that needs only to be copied to produce success. Furthermore, it cannot be presumed that any of the listed methods can be safely applied to any kind of forest just because it is a "recognized standard method."

In summary, this chapter has been an attempt to describe the considerations that enter into the construction of a system; the remaining chapters include discussions of the general categories of systems that foresters have devised. Examples of methods of regeneration and particular silvicultural systems are presented, as is the reasoning underlying their development. These examples are chosen mainly to illustrate application to specific kinds of stands or management objectives. In application, silvicultural systems include a myriad of additional variations designed to accommodate differences in objectives of ownership, accessibility, site quality, and all the other factors that make every stand at least slightly different from all others. Many of these kinds of variations are described and discussed in collections of accounts of silviculture applied to different forest types (US Forest Service, 1983) and regions (Barrett, 1995; Society of American Foresters, 1986) of the United States.

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7

Site Treatments

Introduction

There are three main categories that are used in site treatments: (1) **preparation**; (2) **protection**; and (3) **improvement, conversion**, or **restoration**. When a stand is ready for harvest, foresters sometimes tend to focus their view mostly on the stand to be cut. However, site treatments may be more important in the long run for producing the new stand. The important objective is to prescribe and create environmental conditions appropriate to the establishment and growth of the desired tree species. Efforts can be wasted or damage done if site treatments are either overdone or just automatically applied as a standard method.

The general term **site preparation** is used to describe treatments applied to slash, groundstory vegetation, forest floor, and soil, in order to make the site suitable for natural or planted regeneration and to exclude or reduce competing vegetation. Most of the preparation treatments are applied during establishment, but some are started well in advance of harvest cutting or applied throughout the rotation. The other two site treatments are not necessarily focused directly on tree regeneration. They can be categorized as techniques for protecting the surface soil from erosion and therefore sustaining its productivity, and converting, restoring, or improving site productivity and floristics.

The chapter begins with a discussion of the first step in site treatments, which is usually dealing with the nature and effects of logging debris (**slash**) on the new developing stand. In most instances, all managers are faced with either using, leaving, or disposing of this material prior to regenerating a stand, and treating the site with one or a combination of treatments categorized above. Then various methods of slash removal or redistribution are described. The second part of the chapter describes the actual site treatments in order starting with: (1) the various site preparations to reduce competing vegetation and prepare the site for regeneration from seed or for planting; (2) the techniques for protecting surface soils; and (3) the treatments for site improvement, restoration, and stabilization, where soils and associated vegetation need to be more dramatically altered or rectified.

Several regional manuals have been written on site treatments for establishing regeneration in the southeastern US (Duryea and Dougherty, 1991) and Oregon and northern California (Hobbs *et al*., 1992). These manuals provide more detailed reviews of techniques and practices used in establishing and protecting regeneration, particularly on sensitive sites.

Disposal of Logging Slash

Effects of Slash on the Future Stand

The appearance of slash (the debris left by harvesting operations) is so visually offensive to nearly everyone that it is not easy to be entirely objective about the appropriate extent of disposal. Slash can be both harmful and beneficial; its treatment can be very expensive and the resulting benefits are mostly indirect. The problems created by slash and other organic materials must be integrated whole in terms of their effect on the site (Prescott *et al*., 2000; Aust and Blinn, 2004). It is generally unsightly to cut within or near recreational areas and public roads. Laws often require slash disposal within specified distances from highways, trails, railroads, houses, and adjoining properties (Jones, 1993; Gobster, 1999).

Slash in Relation to Forest Fires

Most slash disposal is still applied primarily to reduce the potential fuel for forest fires (Graham *et al*., 1999; Pollet and Omi, 2002). Slash is a fire hazard because it represents an unusually large volume of fuel and often impedes construction of fire lines. The debris left after a harvest is also potential fuel that would not be there but for the cutting. The greatest problems exist during the short period after cutting, in which the foliage and small branchlets remain on the slash. They can dry out quickly and can ignite and burn rapidly, but larger materials do not normally burn so quickly. Policies of slash disposal have been heavily influenced by the popular misconception that the danger of bad fires on cutover lands can only be stopped by destruction and elimination of logging

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

debris. Actually, the menace of slash can be diminished by any measures that break up its continuity, protect it from sun and wind, or decrease the risk of ignition. The prevalence of fires on heavily cutover areas is thus the result not of the presence of slash but of the desiccation of the exposed forest floor.

When conditions are favorable for very hot fires (e.g., high temperatures, low relative humidity), the dimensions of slash are no longer a factor limiting the rate at which a fire will spread. During bad fire weather, fires can burn rapidly in large concentrations of slash and may turn into uncontrollable conflagrations. The main objective of slash disposal for fire control is the prevention of such catastrophes. Fires on cutover areas almost invariably start and spread in the litter of the old forest floor, and only secondarily spread into the logging slash on top. An area can be rendered temporarily fireproof with the elimination of this blanket of fuel, but the effect lasts only until the first herbaceous vegetation dries out and becomes fuel. Therefore, a good fire-control system is the best method of treating potential fuels.

Effect of Slash on Reproduction

In addition to being a hazard and impediment in fire control, logging debris often hinders the establishment of reproduction. This is caused principally by the heavy shade and the dense concentrations of slash. In such places, advance regeneration is buried or crushed and the establishment of new seedlings is prevented by the shade and potential weevil infestations harbored by slash (Tesch and Korpela, 1993; Devine and Harrington, 2007). Slash composed of green branches is more detrimental than that composed of dead branches because of the heavier shade. The magnitude of the harmful effect depends on the proportion of the area covered, as well as the thickness and density of the slash (Harvey and Brais, 2002).

Thick, dense layers of slash prevent the establishment of reproduction until broken up by decay (Harrington and Schoenholtz, 2010). Sometimes the first plants to appear on the sites of old slash piles are undesirable herbs and shrubs that may take over the growing space for long periods. Thin, loose layers of slash, on the other hand, may be of real benefit to young seedlings by protecting them from extremes of temperature, desiccation, grazing animals, and the competition from shading of intolerant vegetation (Zabowski *et al*., 2000; Egnell and Valinger, 2003). In fact, the complete removal of all potential slash in whole-tree logging can sometimes cause the death of the small advance growth of exposure-intolerant species that have poor sprouting potential, such as the true firs, spruces, and hemlocks. Also, slash disposal is very often done simply to reduce workers' movements when hand or machine planting.

Management of Slash, Litter, and Soil

Logging debris and forest-floor litter can be seen as storehouses of carbohydrates and both organic and inorganic nutrients. They can be left to decay naturally, be burned, or be removed from the site. In recent years there has been a trend to use much of this as an alternative energy source for home heating and power generation, but this can often have consequences with site degradation for maintaining productivity and wildlife habitat (Marshall, 2000; Johnson and Curtis, 2001; Ballard, 2000; Powers *et al*., 2005; Eisenbies *et al*., 2009).

Decisions about how to treat such material depends on the extent to which unincorporated organic matter accumulates on the forest floor. In some conditions that do not favor decomposition, organic matter may accumulate nutrients to such an extent that it may take a hot fire every one or two centuries to rejuvenate the system (Johnson, 1992; Agee, 1993; Johnson, 1998; Prescott, Maynard and Laiho, 2000; Koyama, Kavanaugh and Stephan, 2010; Ebel, 2012). This situation can exist in the fire-ruled kinds of boreal forests in parts of interior Canada (Prescott, Maynard and Laiho, 2000). At the other extreme, certain types of tropical rainforest are on highly weathered oxisols of the continental shield such as the Amazon or Central Africa, where the litter does not accumulate long on the forest floor and almost all of the nutrient capital is continually cycling through the living vegetation (Whitmore, 1990; Richards, 1996; Ashton, 2015). It is important to conserve dead organic matter because the organic part of the system is the only important nutrient reservoir. Most forests lie between these extremes and are places where nutrients are distributed among vegetation, forest floor, and mineral soil. However, the pattern of nutrients and energy distribution varies enough with species and site that a forester should be aware of the particular situation for a stand at the time of any treatment.

If these organic materials are allowed to decay naturally, most of the nutrients are ultimately returned to the soil and living vegetation. In the meantime, they are apt to remain unavailable to the vegetation. Substantial amounts of nitrogen remain bound in the proteins of the microorganisms responsible for the final stages of decay. The effects of immobilization of nutrients can be detrimental on infertile soil or in climates and soils where thick layers of organic matter normally accumulate beneath the forest. If these kinds of dead organic matter decay in place, some of the energy stored in them goes to nourish the large and small soil organisms and are chiefly responsible for maintaining its good physical properties (Wood, 1989; Killiam, 1994). The resulting incorporation of organic matter into the mineral soil is important in maintaining the capacity of the soil to hold water, oxygen, and nutrients.

A layer of slash covering the soil can have beneficial effects on preventing erosion, but not as much as casual consideration might suggest. The prevention of erosion is achieved mainly by getting the water to infiltrate so that it does not run over the surface, picking up organic and mineral fragments. The root channels of living vegetation and porosity of the forest floor materials and upper mineral soil layers are chiefly responsible for the infiltration capacity of forest soils (Brady, 1990; Marshall, 2000). Slash cover does help by decelerating the rate at which snow melts and by preventing rain-splash erosion. However, deposition of slash over actively eroding areas is usually not very effective, except in the cases where it is used as a skid road covering to prevent deep tire ruts from developing.

Effects of Burning on Nutrients and Soil

If dead organic materials are burned, their stored energy goes mostly to heat the air, and the stored chemical nutrients are then released. Some nitrogen compounds are volatilized and lost into the atmosphere, as are carbon, phosphorus and sulphur (Andreae and Merlet, 2001). Most of the nutrient elements that are of mineral origin are returned to the soil in more readily available form than before. Sometimes, depending upon the intensity of the burn, the increased amount of chemical nutrient in the mineral soil stimulates the non-symbiotic nitrogen fixers enough that the supply of available nitrogen becomes greater than before (Harden *et al*., 2003; Thiffault *et al*., 2008; Smithwick *et al*., 2009; Koyama, Kavanaugh, and Stephan, 2010). It is possible for some chemical nutrients, especially nitrate nitrogen and potassium, to be made mobile enough by burning to accelerate loss by leaching and surface runoff (Jordan 1985; May and Attiwill, 2003). In most situations, burning either improves the chemical properties of the soil by accelerating nutrient cycling or does little harm (Walstad, Radoseurch, and Sandberg, 1990; Carter and Foster, 2004).

The effects of burning on the physical properties of the soil range from minimal to harmful (Certini, 2005). They are usually minor because most fires do not burn all the incorporated organic matter, and enough remains to continue most beneficial effects. Severe heating of the mineral soil takes place only where large concentrations of debris or logs burn for an hour or more. This incinerates incorporated organic matter and can cause severe soil damage. In these spots, burning can negatively alter the biological communities of the soil, such as fungal mycorrhizae (Tuininga and Dighton, 2004; McMullan-Fisher *et al*., 2011).

Some soils acquire **hydrophobic** properties (resistance to wetting) because the soil particles get coated with waxy substances. These occur on the leathery leaves of xerophyllic vegetation such as the California chaparral. Hot fires on steep slopes in the coast range of California are responsible for the debris slides that plague that region (DeBano, 2000). These events are rarely found in other vegetation types.

Fire in general can damage forest soils only under unusual circumstances such as combinations of hot fires, steep slopes, and where there has been compaction (DeBano, 2000). The removal of any organic matter from a site inevitably takes away some nutrients and stored energy. Forest systems can replace the energy easily, so that loss becomes serious only if animals or people divert almost all of it away from the soil-improving organisms by excess grazing or farming. The nutrient losses are of greatest consequence because they are harder to replace. Aside from the special case of nitrogen, the available inorganic nutrients of the soil are replaced by decomposition of rock minerals in the soil, mineralization of organic matter, and atmospheric fallout of dust, sea salts, and the products of other forms of air contamination, that are currently often pollutants (e.g., nitrogen) (Goodale and Aber, 2001; Olinger *et al*., 2002; Akimoto, 2003; Krupa, 2003; Chen *et al*., 2010).

Nitrogen compounds come and go from the huge inert reservoir of nitrogen gas in the atmosphere, but virtually none of it is of mineral origin. Most useful nitrogen compounds are captured from the air by nitrogen-fixing microorganisms (Stacey, Burns, and Evans, 1992; May and Attiwill, 2003), but they can also be fixed by lightning discharges and high-temperature combustion (Sprent, 1987). Although available nitrogen compounds are almost always in short supply and a cause for concern, they are more easily replaced by nature than the nutrients of truly mineral origin such as phosphorus (Runyan, D'Odorico, and Lawrence, 2012) (Table 7.1).

Effects of Removing Organic Materials

The organic matter within the soil and on the soil surface of a site is mostly carbon, an element that is now well recognized as an important component in mitigating climate change. Research on carbon in forest soils has been largely limited to temperate biomes in the developed world, and particularly only in the top 12 in (30 cm) of the soil profile. Further, much of the research is focused on agricultural soils (Price, Bradford, and Ashton, 2012). Forest soils in tropical moist regions are represented by only a handful of studies, as are examinations of sequestration of carbon at depth, but perhaps most importantly, the dominant reservoir of soil carbon is at high latitudes and the response of this store to climate change is highly uncertain (Price, Bradford, and Ashton, 2012). Impacts from timber harvesting on soil carbon, at least in temperate forest, are considered to be limited (Yanai, Currie, and Goodale, 2003), but this is likely not the case for tropical forests (Price, Bradford, and Ashton, 2012).

Table 7.1 Probable effects of harvest and site preparation treatments on nitrogen cycling.[1]

Practice	Effects	N-cycle consequences	Probable magnitude
Stem harvests	Removes nutrients, increases soil moisture and temperature, decreases net primary productivity	Decreases uptake Increases mobilization Increases mineralization Increases leaching losses Removal of N in biomass	Moderate Moderate Moderate Small Large
Whole-tree harvest	Removes nutrients, increases soil moisture and temperature, decreases net primary productivity	Decreases uptake Increases immobilization Increases mineralization Increases leaching Removal of N in biomass	Moderate Small Moderate Small Large
Chopping	Crushes slash, kills some competing vegetation	Increases immobilization Decreases uptake	Small Small
Burning	Consumes slash, kills some competing vegetation, blackens soil surface, reduces acidity	Volatizes nitrogen Decreases immobilization Increases mineralization Increases nitrification	Small to large Small Small to moderate Small
Root raking, blading, windrowing	Concentrates slash in rows, moves forest floor and topsoil into rows, exposes mineral soil, controls competition	Redistributes nutrients Decreases immobilization Decreases mineralization Decreases uptake Increases fire loss	Large Small Moderate Small Large
Disking	Mixes forest floor and topsoil, reduces compaction, increases aeration, and controls competition	Increases erosion Increases mineralization Increases nitrification Decreases uptake	Moderate Moderate Moderate Small
Bedding	Plows soil into raised rows, creating aerobic zone adjacent to anaerobic zone	Increases mineralization Increases nitrification Increases de-nitrification	Small to moderate Small to moderate Small
Herbicide	Inhibits competing vegetation	Decreases uptake	Small

1) A small effect would involve N losses equal to less than the annual N uptake in the ecosystem; a moderate effect would involve losses equal to several times annual N uptake; and a large loss may be 10 times or more greater than annual uptake.
Source: Adapted from Binkley, 1986.

When nutrients are removed from soils and biomass during harvesting, their replenishment comes from organic matter decomposition and mineralization, and from the relatively slow processes of rock weathering and atmospheric deposition (and biological fixation in the case of nitrogen) (Perry *et al.*, 1989; Gessel *et al.*, 1990). If nothing but stemwood larger than 4 in (10 cm) is removed, nutrient depletion is seldom likely to be of consequence. The large stemwood is a major part of the energy storage (i.e., carbohydrate), but it contains low proportions of nutrients (Hendrickson, Chatarpaul, and Burgess, 1989; Eisenbies *et al.*, 2009). Most of the mass of wood consists of molecules of cellulose and lignin, which are composed only of carbon, hydrogen, and oxygen. Usually, the nutrients lost in stemwood harvests are roughly equivalent to the time it takes for the new stand to grow the same amount of wood. Although this balance of nutrient loss and subsequent nutrient input generally holds, there is no inherent reason why it should. It is dangerous to assume that it will in cases where the rock weathering cannot act as a source of newly available nutrients. Examples of low-nutrient sites include peatbogs (Paavilainen and Paivanen, 1995), sands composed largely of silicon dioxide such as spodosols (Jordan 1985; Whitmore, 1990), and the strongly leached soils of certain tropical rain forests (Vitousek and Sanford, 1986; Feldpausch *et al.*, 2004; Jobbágy and Jackson, 2004).

In the most common condition, the nutrients are concentrated in the leaves, twigs, rootlets, bark, and especially the litter layers of the forest (Eisenbies *et al.*, 2009). Often there is also a large nutrient reservoir in the mineral soil. If these materials are left on the ground or burned in place at the time of harvest, no soil damage is likely. However, if they are removed for utilization or pushed too far to the side, varying degrees of nutrient depletion can result (Duryea and Dougherty, 1991; Aust and Blinn, 2004).

The annual removal of the litter for fuel or agricultural mulches, common where land resources are overstrained, is one of the most damaging things that can be done to forests and their soil. This activity is particularly prevalent in the oak–pine types of the Himalayas and the central mountains of Mexico (Thadani and Ashton, 1995). It leads not only to nutrient depletion but also to serious erosion because the supply of the soil-improving organisms is diverted away from them (Brady and Weil, 1996). It is possible to develop guidelines for sustainable levels of litter removal in specific forest types, as is being done for collection of slash pine litter (called "pinestraw") in Florida, for use as a landscaping mulch (Duryea and Dougherty, 1991).

Some of the same kinds of problems could result from very close utilization of forest production by whole-tree chipping for fuel, pulp, and animal food (Vitousek and Matson, 1985; Hendrickson, Chatarpaul, and Burgess, 1989; Olsson *et al*., 1996). These purposes do not require removing the litter, and there is little use in removing green leaves except for their food value. The extent of any problems depends on how much of the vegetative structures are removed from the site and how frequently they are removed. Fertilization may be needed to replace nutrient losses, but timber harvesting depletes nutrients much less than agriculture or grazing. The need for replacement of nutrient losses by fertilization may be anticipated, although at rates far less than those common in agriculture.

The problem of nutrient depletion during harvesting can be avoided by trying to leave the leaves, twigs, and small roots where they grew (Vitousek and Matson, 1985; Olsson *et al*., 1996). Their high content of water and poor fiber characteristics make them more valuable for their nutrient content than for fuel or pulp. These small twigs, branches, and leaves are often chipped, but that procedure is done just to avoid the cost of delimbing the large branches. Furthermore, fire and even herbicides are kinder to the soil than almost any mechanical treatment. These observations are contrary to popular intuition, but they are true so long as forest systems are understood and not pushed beyond the limits of their rotation or the efficiency of their utilization (Aust and Blinn, 2004; Eisenbies *et al*., 2009).

Effects of Burning Forest Fuels on the Air

The most important problems associated with smoke from forest fuels are from unburned particles that make it a human health pollutant that also restricts visibility (Andreae and Merlet, 2001). Therefore, air quality is better when fuels are dry, and combustion is quick and complete. Furthermore, the conditions for good combustion are usually those in which smoke columns rise quickly so that the ash pollutants are soon dispersed thinly in the atmosphere. This occurs when air becomes colder with increasing height. If there is a temperature inversion (that is, a situation in which warm air has settled above cooler air), the smoke will accumulate beneath an otherwise invisible ceiling formed by the warm air and this can become a significant health hazard in populated regions. Most prescribed burning is very localized and timed to avoid such problems, but large wildfires can cause significant particulate pollution across wide regions of a continent that are hazardous to human health (Wotawa and Trainer, 2000; Sapkota *et al*., 2005). Many urban–forest interface regions now have burn restrictions or bans because of this (Wiedinmyer *et al*., 2006).

Unfortunately, the atmospheric conditions that dilute the smoke most rapidly are the same as those that create the dangerous spread of fires. Therefore, compromises have to be made, and these reduce the number of days when silvicultural burning is possible. Greatest care is needed where the spreading of fire would do great harm or where the spreading of smoke would cause dangerous restrictions of visibility along highways or at airports. In most cases, special permits are required for such burning. It is at all times necessary to coordinate the operations with the best available knowledge about how the weather conditions will affect the behavior of fires and the smoke from them. Small amounts of noxious gases, mostly carbon monoxide, are produced by burning forest fuels, but they are so quickly diluted that there is little evidence of harm caused by them. As is the case with the dirt from unburned particles, production of noxious gases arises from poor combustion. In this respect, cool, smoldering fires are more harmful than hot, quick, vigorous ones.

Most of the smoke generated from forest fuels come from wildfires (often ignited by people either by mistake or intentionally) or land-clearing fires. Many forests grow in seasonally dry climates in which it is not a question of whether the forest fuels will burn but of when and under what conditions.

Both burning and decay of organic substances from the forest and elsewhere changes the carbon into atmospheric carbon dioxide. There is concern that continuing increases in the amount of this gas in the atmosphere will block so much outgoing radiation as to cause significant climatic warming. Unfortunately, it does not appear that the increased carbon dioxide goes entirely toward making the world's vegetation grow faster because the amount in the atmosphere is increasing. There is a net transfer of carbon to the atmosphere when forests are destroyed and not replaced with new ones (Dale, Houghton, and Hall, 1991; Covey, Orefice, and Lee, 2012). However, forests that are actively accumulating wood are removing carbon dioxide from the air (Covey, Orefice, and Lee, 2012), and wood that is put to structural use continues to sequester carbon

(Larson *et al.*, 2012). Silviculture, especially that aimed at timber production, is not a cause of this problem but is potentially at least a partial solution (Ashton *et al.*, 2012).

Slash in Relation to Insects, Fungi, and Wildlife

The insects and fungi that feed on logging debris are more beneficial than harmful because they are primarily responsible for the decay of unburned slash (McCullough, Werner, and Neumann, 1998; Niemela, 1999; Fettig *et al.*, 2007). The vast majority of them are scavengers or saprophytes that do not attack living trees. The few species of bark beetles (e.g., pales reproduction weevil) and heart-rotting fungi that can spread from slash to living trees are found mostly in the cull logs, stumps, and large branches that are rarely eliminated in conventional slash disposal. The injurious fungi that proliferate in large pieces of slash are those that have already infected the living trees. Some of them produce fruiting bodies more abundantly after cutting than in living trees. The treatment of slash to control insects and fungi is best accomplished by such measures as close utilization, and indirect methods of combating the proliferation and spread of harmful organisms through such techniques as the use of pheromone traps (Roth, Shaw, and Rolf, 2000).

Ordinary slash burning does not necessarily have any effect on the situation, and may even aggravate it by killing unmerchantable standing trees and impacting beneficial fungal communities (Sapphire *et aI.*, 2011). The most important aspect of the influence of insects and fungi on slash is the rate at which they bring about decay (Fettig *et al.*, 2007; West *et al.*, 2008). It may take from several years to several decades for slash to decompose, depending on climate and species. The question of how much time is required has important bearing on whether or how to treat the slash and also on the planning of future operations.

Hardwood slash tends to remain moist and decays so rapidly that it is seldom necessary to burn it. Slash generally decays more swiftly on good or moist sites than those that are extremely wet or dry, and partial shade is conducive to decomposition. In temperate moist hardwood forests, slash may take 10–20 years to decompose, but woody debris can stay for much longer, such as for softwood in the dry inland west.

For many wildlife species, slash can create novel foraging habitat and cover for rodents, ground nesting birds, and salamanders, particularly if the slash is scattered or left in small piles with a distribution of larger culls left on site (DeGraaf and Yamasaki, 2001). However, slash should not be deposited in waterways because its decomposition may reduce the oxygen content of the water below the level required for many species of fish (Aust and Blinn, 2004). These effects are described in Chapter 24, which covers wildlife habitat.

Slash in Relation to Harvesting Operations

Efficiency in log transportation depends to a large extent on the success with which slash is concentrated during felling. The interests of both logging and silviculture work best when the slash is distributed in a large number of small compact piles or in long, narrow strips. The consolidation of slash into a few very large piles is as detrimental to silvicultural purposes as the diffuse scattering of debris is to efficient movent of logs (Aust and Blinn, 2004). There are occasions when the slash from one cutting may remain long enough to disturb later operations. However, with current logging machinery, it is now common to scatter slash with it being left untouched. This is the best procedure for decomposition, soil protection, and microhabitat. However, in the end, the amount of logging residue and the diameters of its components depend on the extent of utilization of the felled trees. Large, untrimmed treetops can be detrimental (Harvey and Brais, 2002): in fire-prone climates they can cover a lot of space, and their loosely arranged twigs and foliage allow fires to travel rapidly (Devine and Harrington, 2007). Increased intensity of utilization reduces the amount of large debris. Moreover, it almost automatically ensures that any fine fuels that remain are left more compact and closer to the ground so that they burn more slowly and decay faster. Debris can also be distributed on trails to reduce compaction when skidding on soils that are wet or fine textured, and this is commonly done (Aust and Blinn, 2004).

Methods and Application of Slash Disposal

Tremendous advances in fire control and more complete wood utilization have caused slash disposal to be a forestry practice that is becoming less important. When it is practiced, it is often for the purpose of facilitating planting or natural regeneration, and ensuring that enough slash is left for wildlife habitat and long-term soil productivity (Johnson and Curtis, 2001; Laclau *et al.*, 2010).

Slash disposal for fuel reduction is common practice in western North America, which has long, rainless summers. Most of it has been done by cheap broadcast burning (Walstad, Radoseurch, and Sandberg, 1990) but with air pollution, wildfire risk, and the ecological value of retaining coarse woody debris, more controlled measures of piling and burning are now commonly practiced. In this region and others, slash is left only in narrow bands along travel routes or at intervals across cutover areas in order to break up concentrations and provide places for fire-line construction.

In most other parts of North America, the disposal of slash for fire control has not been as necessary. In the northern coniferous forests, limited kinds of slash disposal are sometimes desirable. In the southern pine forests, slash rots so quickly that it rarely requires treatment,

but it is sometimes used anyway, mainly for the purpose of preparing the seedbed for regeneration. In the eastern hardwood forests and in the northeast, slash also rots quickly enough that disposal is required only along roads and in similar places for aesthetic concerns.

Broadcast Burning of Slash

In broadcast burning, the slash on clearcut areas is burned as it lies within prepared fire lines. Practically all the remaining vegetation, except for that of sprouting species, is destroyed. This removes any advance reproduction but it eliminates most of any undesirable vegetation that may be present. The extent of exposure of mineral soil is actually rather variable, depending on the moisture content of the forest floor at time of burning. Usually an ample amount of mineral soil is exposed. The sites are left in reasonably good condition for hand planting, direct seeding, or natural seeding from adjacent stands where light-seeded species require exposed mineral soil for best germination.

Broadcast burning was often associated with the historical clearcutting of old-growth stands in the west (Fig. 7.1) which is rarely practiced now. It can also be applied where scattered fire-tolerant seed trees, such as western larch, have been reserved, provided that fuel is removed from around the base of the trees. Unless some source of wind-dispersed seed is close by, broadcast burning is generally used only with planting. It is usually important to set the fires quickly under just the right conditions and in patterns that will cause the fires to burn away from the edges. Treatments can be expedited by dropping incendiary devices from aircraft.

In the southeastern US, broadcast burning to prepare sites for pine plantings is still done, but studies show the effect on nitrogen loss to be significant (Carter and Foster, 2004). The amount of nitrogen lost from broadcast burning is related to the amount of fuels consumed, and it appears to exceed the rate of replacement by natural processes, thus necessitating regular fertilizer application. If the fires can be controlled, it may be enough to reduce broadcast burning to concentrations of slash in **spots** or **patches**. Sometimes this is a way of conserving seeds that have already fallen or of reducing any harmful effects of slash burning. In many regions of the US fire is avoided because of liability associated with roadways and vehicular accidents. On industry lands, burns within timber plantations are rarely used to control understory brush growth because of its potential to damage the overstory and the considerable investment made in plantation establishment (e.g., genetic tree improvement, fertilization, and weed control).

Burning of Piled Slash

Slash disposal associated with partial cutting usually involves the burning of piled slash. Where this sort of work is necessary, it is ordinarily done by pushing the slash into piles with bulldozers or similar equipment for burning. Use of this equipment has the important advantage of reducing the competing vegetation and exposing the mineral soil on the treated areas. This effect makes an important contribution to the success of natural regeneration or planting where competition from brush is a serious problem after partial cuttings, as in the mixed conifer types of the Sierra Nevada (Fig. 7.2). The older

Figure 7.1 Broadcast burning in preparation for planting after clearcutting a mature stand of western white pine, western hemlock, and fir, Deception Creek Experimental Forest, Idaho. Note the large volume of defective grand fir and western hemlock felled before the burning. If this had been left standing, resulting dead snags might have become ignited in wildfires and spread burning embers far and wide. *Source:* US Forest Service.

(a)

(b)

Figure 7.2 **(a)** Dense, 6-year-old natural regeneration of ponderosa pine resulting from very intensive site preparation at Blacks Mountain Experimental Forest on the eastern slope of the Sierra Nevada. Most of the slash was piled mechanically in windrows along the edge of the opening, which was created in a group-selection cutting. During the next good seed year the area was disk-plowed. *Source:* US Forest Service. **(b)** An example of a pile-and-burn treatment in a western larch and ponderosa pine stand in western Montana that had an establishment cut of a seed-tree regeneration method, where the slash has been piled and the site scarified. Piles will be burned in the early spring when snow is still on the ground to prevent any possibility of escape. *Source:* Mark S. Ashton.

methods of expensive handpiling have little silvicultural effect other than freeing advance regeneration and exposing some mineral soil. As far as the techniques are concerned, **progressive burning**, is when the slash is laid on piles as the burning progresses, and **piling and burning**, is when the piles are constructed well in advance of the time when it becomes safe enough to burn them. Piling of slash without burning is often useful for maintaining certain wildlife species that require protection and denning or nesting places under circumstances that otherwise would be open. This is a common practice on industry land in the south. If such work is done by hand, the cost can be kept in check by planning to move the material over only short distances to many

small piles. However, the burning of small piles of slash can be very costly, partly because workers easily become mesmerized watching the fires!

Mechanical piling is quite useful for the open forests of the interior ponderosa pine type, provided that the terrain is not too steep or rocky. The opportunity to dispose of large slash material in which bark beetles might breed is important for ponderosa pine management. Mechanical piling has also been used after clearcutting in the lodgepole pine type. It has produced good fuel reduction and better reproduction than broadcast burning. Recent research emphasizes the need to build many small piles that are burned after snowfall in these forest types. Large piles that build intense heat can change microbial communities and site productivity in localized patches for long periods of time (Jiménez-Esquilín *et al*., 2007). Korb, Johnson, and Covington (2004) recommend post-burn applications of soil–seed ammendments to the burned surface area to ameliorate such sites.

Lopping and Scattering of Slash

Some objectives of slash disposal can be accomplished without burning. The fire hazard can be reduced simply by lopping the tops so that the branches lie closer to the ground. Lopping can be advantageous in freeing saplings and seedlings of advance growth that have been bent over by falling tree tops. A limited amount of this kind of work may reduce the necessity for planting or waiting for new natural reproduction and forestalls subsequent difficulties with malformed trees. Bent trees should be released as promptly as possible; they straighten up much better at the beginning of the growing season than if they are not given an opportunity to do so until growth has been going on for several weeks.

Although lopping is one of the cheaper forms of slash disposal, anything that involves scattering or moving slash can be rather expensive. Lopped slash is sometimes scattered and kept below about 18 in (45 cm) of the soil surface to facilitate decomposition in instances where any sort of burning would destroy too much advance reproduction. The deliberate scattering of slash provides an artificial means of seed dispersal for closed-cone conifers (jack and lodgepole pine), especially in clearcut and large open areas where no nearby standing tree seed source is available. It is also possible to break up concentrations of slash or eliminate it in strips along travel routes simply by moving it. Such methods have been found useful in areas of the forest–urban interface, where prescribed burning would be too risky but the lopping and scattering of slash is a feasible alternative (Kalabokidis and Omi, 1998). None of these techniques of redistributing slash reduces the total amount of fuel. However, they are often more compatible with silvicultural objectives than methods involving burning, especially in situations where the risk of wildfire is not very great.

Chipping and Yarding of Slash

Portable chipping devices are sometimes used where slash disposal is essential but burning is prohibited, or for some reason is not possible. Such devices are, of course, most useful when the chipped material can be utilized for pulp, biofuel, or mulch. Slash disposal problems can sometimes be mitigated by transporting large unmerchantable material along with merchantable logs to central landings. The resulting concentrations can be either burned at these points or stored where they will be accessible when market conditions permit their utilization.

Treatment of the Forest Floor and Competing Vegetation

The establishment and development of a new forest stand can take place only if sufficient growing space is made available by harvesting, or by killing all or part of the existing stand, and any sort of regeneration from seed is affected by the condition of the seedbed. Basic requirements can sometimes be met by the pattern of cutting, by intentional or unintentional disturbance in logging, or by treatments of undesirable vegetation that are delayed until after the reproduction is established. Deliberate measures such as prescribed burning, mechanical site preparation, or herbicide applications are sometimes necessary to create the appropriate environmental conditions for natural or artificial reproduction. Site treatments can be categorized into: (1) those where exclusion of competing vegetation and preparation of the seedbed are necessary for planting or seed germination; (2) those treatments that are chiefly intended to protect the site and soil surface but no more; and (3) those treatments that are designed to change the actual condition of the site by improving, converting, or restoring the fundamental hydrology or soil fertility. All treatments can be functionally described by one or a combination of the following: (1) protection, (2) competive exclusion, (3) ameliorization, (4) infiltration, and (5) stabilization (see Table 7.2; Fig. 7.3).

Site Preparation of Competing Vegetation

The harvesting of trees inevitably leaves vacant growing space, at least temporarily. After a very heavy cutting there may be serious competition from unwanted vegetation. Unless the markets are good, there is certain to be a residue of trees that are not worth cutting. There may also be low vegetation consisting of grasses, herbaceous plants, shrubs, or advance growth of undesirable tree species. If no vegetation shows aboveground, there may still be rootstocks of sprouting species. Finally, if little or no vegetation remains and if the site is reasonably

Table 7.2 Examples of site treatments that can facilitate the germination and establishment of different kinds of natural regeneration and planted seedling stock.

Mode of regeneration	Associated site treatments
Advance regeneration (non-masting)	
Shade tolerant, fire sensitive Species example: red maple, sugar maple, balsam fir, white fir Regeneration method: shelterwood/single or group selection	Minimal site treatments needed in most cases; sometimes use of herbicide or cutting out understory competition may be necessary
Advance regeneration (masting)	
Intermediate to intolerant of shade Species example: oak, hickory Regeneration method: shelterwood/group selection	Usually site treatments are needed to remove the understory by herbicide or cutting; prescribed burning of the understory can be used to control vegetation and encourage re-sprouting of fire-hardy advance regeneration
Vegetative sprouts	
Shade intolerant Species example: aspen, chestnut Regeneration method: coppice	Minimal site treatments needed. In some cases chopping and crushing may be necessary to level the slash to encourage uniform sprouting
Long-lived pioneer (wind-aided dispersal)	
Shade intolerant and fire tolerant when established Species example: Douglas-fir, longleaf pine Regeneration method: seed tree/patch selection	Chopping and crushing brush, followed by a prescribed broadcast burn or pile-and-burn with scarification
Long-lived pioneer (buried/stored seed bank)	
Shade intolerant and obligate fire germinant Species example: lodgepole pine, jack pine Regeneration method: true clearcut	Broadcast burn of scattered slash to release seeds from cones, or scatter slash exposed to summer heat with some scarification
Planted seedlings on an upland site	
Shade intolerant Species example: loblolly pine	Chopping and crushing brush followed by ripping and bedding. After planting, an application of herbicide may be necessary to keep the grasses and herbaceous vegetation down
Planted seedlings on a poorly drained site	
Intermediate to intolerant of shade Species example: northern white-cedar	Chopping and crushing. Drainage ditches and/or pit-and-mound. Plantings on side drainage of mounds for best rooting

Source: Mark S. Ashton.

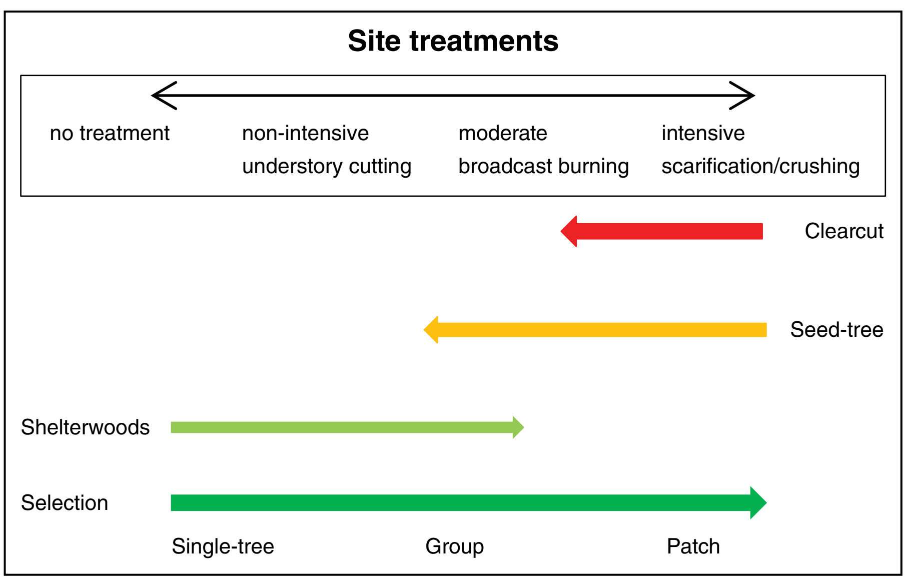

Figure 7.3 A conceptual diagram illustrating the intensity of site treatments associated with methods of natural regeneration. *Source:* Mark S. Ashton.

Figure 7.4 An old-field stand of shortleaf pine invading abandoned agricultural land in the Arkansas Ozarks. Because the grass inhibits broadleaved species more than conifers, the new pine stand will be unnaturally pure. *Source:* US Forest Service.

favorable for plants, the way is open for invasion by all sorts of light-seeded wind- or water-dispersed plants or a release of germinants from a soil seed bank (Royo and Carson, 2006). The most serious problems arise when the competing vegetation has existed for many years and is not worth harvesting at all. The low shrubs of brushfields and the grasses or other herbaceous growth of "open" lands do not cast as much shade as a closed forest, but can cause even more root competition as far as seedlings are concerned (Putz and Canham, 1992; Hill, Canham, and Wood, 1995; Royo and Carson, 2006). Consequently, unwanted preexisting vegetation most likely will have to be controlled when it is so worthless that planting is necessary (Royo and Carson, 2006).

Grass, ferns, and other low vegetation hamper the growth of trees more than might be inferred from their comparatively short stature (de la Cretaz and Kelty, 2002; Slocum *et al*., 2004). Last year's grass or fern, lying brown and battered on the ground at planting time, can be deceptive and should be assessed in terms of the height it attains in the growing season. Tall, dense grasses, herbs, and fern often compete with tree seedlings enough for physical space, soil, water, and nutrients to significantly reduce survival (Balandier *et al*., 2006). Grass competition is almost always problematic if there are serious seasonal moisture deficiencies (Perry *et al*., 1994). For example, it is the chief cause of the "grass stage" of longleaf pine and of "check" in planted spruce, conditions in which seedlings have to grow significant root systems first to overcome surrounding vegetation competition. Where the forest canopy is deciduous or has allowed more light to the forest floor because of continuous canopy disturbance, woody evergreen shrubs can dominate the groundstory. Their competitive effects can inhibit establishment of advance growth of canopy tree species (Tesch and Hobbs, 1989; Lorimer, Chapman, and Lamber, 1994; Ducey, Moser, and Ashton, 1996).

Not all of the effects of grass or other inhibiting vegetation are from competition for light, water, and nutrients. There is a growing body of evidence about **allelopathic effects**, which are chemical antagonisms between different species that enable one species to inhibit the progeny of other species, or sometimes its own (Ward and McCormick, 1982; Rice, 1984). The effects of competing vegetation can be useful as well as harmful. Eastern North America has vast areas of unnaturally pure stands of various pines and spruces that spontaneously reforested abandoned grassy fields and are testimony to the ability of grass to exclude many hardwood species (Fig. 7.4) (Larson, Patel, and Vimmerstedt, 1995). Some of this was the result of selective grazing, but much of it was probably from the competition and allelopathic effects of grass and fern (e.g., hayscented fern, bracken fern). Such effects have been demonstrated elsewhere in the tropics with the *Imperata* grasslands of Asia (Otsamo, 2002) and in boreal forest (e.g., *Calamagrostis canadensi*) (Zackrisson and Nilsson, 1992; Lieffers, MacDonald and Hogg, 1993). These effects of grass can be great enough that planted stands of hardwoods may have to be cultivated like row crops during the first year or two.

In the southeastern US, first the annual and then the perennial grasses that normally appear after burning or mechanical site preparation probably serve to inhibit hardwoods. This is on areas being treated to regenerate pine, so the effect may be beneficial. This effect has been deliberately used to inhibit reinvasion by the native angiosperm forest in the Jari Valley of Amazonian Brazil after it was clearcut and replaced by planted Caribbean

pine (Evans, 1984). In silvo-pastoral systems, browse preferences of cattle to grasses and clover can increase pine survival (Pearson, Baldwin, and Barnett, 1990).

More generally, the establishment of forest trees is often assisted by the temporary protective effects of other vegetation, especially the herbaceous kinds. Such cover may be essential in preventing damage by heat or frost when the tree seedlings are very young and succulent. The theoretically ideal kind of accessory vegetation would be that which protected but did not compete. Mosses, which are not capable of pulling water and nutrients from the soil, sometimes come close to this ideal. The next best would be plants that died or became overtopped by young trees promptly after their protective effects were ended. Even this does not always help. The insulating effects of a grass cover can, for example, cause frost damage to hardwoods after they emerge and are exposed to the much colder air above it.

It must be fully anticipated that any lethal disturbance done deliberately or unintentionally in the process of forest regeneration will cause the appearance of some kinds of vegetation other than the species desired. Treatments that expose the mineral soil to sunlight inevitably produce pioneer vegetation. The forester who carries out such treatments must have full knowledge of what this kind of vegetation will be, and should be ready to live with the consequences. Any treatments that eliminate all or most of the preexisting vegetation usually fit best with the regeneration of species that are naturally adapted to follow fires. If the object is to regenerate shade-tolerant species that are not so adapted, such treatments may worsen the situation by bringing in too much undesirable vegetation.

It is important to know the kind of vegetation that will develop after any kind of treatment (e.g., interactions with understory species, selective browse affects). If the preexisting vegetation is going to hamper the establishment of a new stand of trees, it is usually best to eliminate as much of it as necessary before the regeneration step than to try to control it afterward. Except for broadcast herbicide spraying, most kinds of selective weeding treatment are costly and cumbersome. In the past, it has often been impractical to provide young trees with anything approaching complete freedom from competition. Herbicides and heavy mechanical equipment have now provided the power to kill the roots of competing vegetation. The spectacular increases in seedling growth that can be attained by these treatments have been observed in a wide variety of species and regions.

Techniques of Treatment

Prescribed burning, mechanical site preparation, and flooding are techniques in which both the forest floor and competing vegetation can be treated simultaneously. Before considering these three methods in detail, attention is given to other means of accomplishing the objectives. Some scarification of the mineral soil and reduction of competing vegetation can be accomplished during logging as well as any disposal of slash. Although the resulting disturbance is often adequate, it seldom exposes any substantial amounts of mineral soil or eliminates much sprouting vegetation. Logging does not result in very complete scarification unless there is a deliberate attempt to skid almost every log over a different pathway on snow-free ground. Broadcast burning often eliminates most of the unincorporated organic matter but does not necessarily reduce sprouting vegetation very much. The one kind of slash disposal that is most likely to achieve complete site preparation is that in which the slash is piled with bulldozers equipped with root rakes or similar equipment, but it is the treatment most susceptible to degradation. Practically all of the other methods of logging or slash disposal have limited and erratic effects.

There is no silvicultural treatment other than those mentioned that significantly interrupts the continuity of the forest floor, but there are a number of ways of attacking the competing vegetation. Most of these, such as cutting, girdling, and chemical treatment, are considered in Chapter 20. Cutting, girdling, and fire are entirely adequate for species that do not sprout. Herbicide treatments can be used to eliminate almost all vegetation from most kinds of sites but this method is generally expensive and cannot always be selective. The combination of two or three methods of plant killing in sequence is often cheaper and less harmful than reliance on use of one treatment.

Grazing and browsing animals are sometimes selective enough in their feeding to cause moderate and temporary reduction of competing vegetation. Most of the grasses and other plants on which they feed are capable of sprouting. Feeding that is heavy enough to substantially reduce the competing vegetation is often associated with effects harmful to tree seedlings. Nevertheless, regulated herds of domestic animals can sometimes be used to control undesirable vegetation without suffering from malnutrition (Pearson, Baldwin, and Barnett, 1990).

Treatments to exclude competing vegetation can be categorized as: (a) herbicides; (b) browsing animals; (c) prescribed burning; (d) flooding; (e) mechanical techniques. They are described in an order that reflects degree of intensity and impact of treatment on the site with application of judicious use of herbicide having the least impact and the most intense mechanical treatment, such as deep plowing, having the greatest impact (see Table 7.2).

Herbicide Treatments

As is evident from the previous discussion, herbicides can also be an important part of site preparation (Allen, Fox, and Campbell, 2005; Fox, Jokela, and Allen, 2007; Wagner *et al.*, 2006). The general use of herbicides is described further and elaborated upon in Chapters 18 and 20 with regard to silvicultural tools and release

treatments. However, much of that discussion applies to this chapter as well. In site preparation uses, the need for selectivity among species is often absent, so achieving results is not as complicated as it is with release treatments (see Chapters 18 and 20) (McCormack, 1991). It is possible to kill all low vegetation on a site with aerial or broadcast spraying, but girdling or cutting of larger trees would be needed. However, herbicide removal of competing vegetation has no effect on forest floor conditions; thus it is not appropriate as the sole treatment for many situations. In addition, the costs of herbicides themselves and the application of labor and equipment are so high that other methods may be preferable. In certain circumstances, the use of alternatives may be more desirable merely to avoid regulation or public controversy, especially on public lands. In any case, it is often better to use herbicides in combination with other techniques (McCormack, 1994; Wagner *et al*., 2006). Two examples can be cited: (1) when not enough fuel is present to carry a fire, fairly low doses of herbicides can be used to top-kill the low vegetation, and after drying, it will allow burning; (2) roller chopping will scarify soil and break up tops of vegetation causing sprouting, and then spot applications of small amounts of herbicides to new sprouts will be effective (Allen, Fox, and Campbell, 2005).

In North America, the most obvious use of herbicide applications is on herbaceous and woody vegetation that competes with planted or natural regeneration of conifers. Examples are: boreal spruce–fir–pine (Wagner, Mohammed, and Noland, 1999; Man, Rice, and MacDonald, 2009; Pitt *et al*., 2010); Douglas-fir (Maguire *et al*., 2009); loblolly and slash pine (Allen, Fox, and Campbell, 2005; Fox, Jokela, and Allen, 2007). Such applications are a broadcast selective herbicide mixture that is sprayed on the site at a time and in a way that avoids killing the planted or naturally regenerating conifers, but kills grasses, ferns, forbs, and woody broadleaf tree regeneration and shrubs (Allen, Fox, and Campbell, 2005; Fox, Jokela, and Allen, 2007; Wagner *et al*., 2006).

In temperate hardwood forests, herbicide treatment is little used for preparation of the site unless it is applied to the surfaces of cut brush and cut stumps to reduce sprout competition with advance regeneration or planted seedlings (e.g., red maple sprout growth with planted red oak) (Groninger *et al*., 1998; Kochenderfer *et al*., 2001). However in recent years, herbicide use has become one of the most important controls of exotic invasives for site restoration, particularly in rangeland ecosystems (DiTomaso, 2000) and temperate hardwood forests (Webster and Jenkins, 2006). This new area of application may be one of the most important tools for native species and ecosystem conservation (Wagner *et al*., 2004), particularly in removing clonal understory invasive shrubs and herbs that have replaced the growing space needed to secure advance regeneration in site-preparation techniques preceeding regeneration establishment in shelterwood and selection systems such as these, including barberry, rhododendron, garlic mustard, hayscented fern, and multiflora rose.

Use of Browsing and Grazing Animals

Livestock and game that eat competing vegetation have been used widely in forested regions that include more open habitats, namely drier, seasonal climates of woodland and pine where groundstory forage is more abundant. Examples are from the Intermountain regions of North America, Mediterranean, and Eurasia. Knowledge of browsing preferences (usually conifers are less desired than hardwoods) and growth phenology (young, succulent shoots are more desirable than woody shoots) can be used to allow browsing and grazing animals to selectively reduce competing vegetation, and increase soil water availability for desired planted or natural regeneration. Traditionally this has been used to facilitate pine growth from competing hardwoods (Karl and Doescher, 1993). In addition, in circumstances where fertilizer has also been applied, much of the fertilizer benefit can be allocated to vigorous competing vegetation. The use of animals may readjust such effects by reducing this vegetation and re-allocating the nutrients to the target plants through manure (Adams, 1975). However, recent results have been mixed, with some studies that have shown detrimental effects (e.g., large animals laying down on regeneration), others that have shown no effect of grazing as a site treatment, and still others that have demonstrated improved establishment of regeneration (Heineman *et al*., 2005). Many of the older studies showing positive effects were often poorly designed (Heineman *et al*., 2005).

Prescribed Burning

Prescribed burning can be applied in many different ways as a site-preparation technique. It can be used as a technique that kills or promotes the dieback of understory shrubs and clonal fire-sensitive herbs that impede establishment of advance regeneration (Carter and Foster, 2004). Doing such kinds of burns are useful in preparing and facilitating the understory of a forest for establishment of fire-hardy advance regeneration (Moser, Ducey and Ashton, 1996; Carter and Foster, 2004). An obvious example of a forest type in North America are the oak woodlands of the prairie states (Peterson and Reich, 2001). Burning in this manner in wetter climates of the Appalachian temperate hardwood forests will also promote oaks over such species as birch and maple, and understory shrubs, such as laurel and rhododendron (Abrams, 1992; Knoepp and Swank, 1993; Moser, Ducey, and Ashton, 1996). However, hotter ground fires on more droughty sandy soils will often promote more fire-tolerant hard pines, such as pitch pine, slash pine, longleaf pine (Glitzenstein, Platt, and Streng, 1995; Gilliam and Platt, 1999; Menges and Deyrup, 2001;

Brose and Waldrop, 2006) at the expense of oaks and other hardwoods (Gray and Dighton, 2009).

The hottest broadcast fires that purposely burn logging slash after clearcutting not only reduce impeding organic debris, but serve to expose mineral soil necessary for germination of light-seeded species, control herbaceous and sprout growth of competing vegetation, and release a flush of nutrients available for new regeneration (Carter and Foster, 2004). When it is hot enough, such a fire can emulate in a simplistic way the kind of environment that a stand-replacing fire might create. Such fires are suitable for forest types that are adapted to stand-replacing fires in interior continental Intermountain and boreal regions (e.g., jack pine, black spruce, lodgepole pine, Englemann spruce) (Johnson and Fryer, 1989; Barrett, Arno, and Key, 1991; Hesketh, Greene, and Pounden, 2009). As mentioned previously, these fires need to be hot, but quickly burn only the surface fuels. Smoldering fires that burn deep into the mineral soil for long periods of time can be very detrimental.

Prescribed burning is often done in combination with application of herbicide or in more controlled ways to primarily remove slash and to reduce risk of wildlfire or soil degradation effects by piling and burning if not carefully managed. In this case, mineral soil exposure can be done with mechanical treatments. More detailed accounts of using fire as a silvicultural tool are described in Chapter 18.

Flooding

Flooding is a treatment that is rarely used in North America, but is used in many other places in the world. Flooding is used to exclude plant competition and prepare the site for seeding or planting. Many regions have intensively controlled coastal and riparian lands. Water guided by channels and dikes is directed to seasonally inundate a site to kill off weed growth. After several weeks, these lands are drained and sites are prepared. The obvious example is the practice of paddy cultivation for rice. Another example is the integration of forestry with aquaculture, such as the shrimp ponds and mangrove plantations of some parts of coastal Indonesia.

This might appear novel, but many tree species along rivers, swamps, and coastal margins rely on seasonal flooding as a disturbance regime that promotes their dispersal by water and subsequent colonization on newly opened growing space after the waters recede. This in effect is done in bottomland hardwood forests throughout the southeastern US, where fine silts and clays are deposited across extensive flood-plains and backwaters of large river systems, after which certain species of maple, gum, water oak, and hickory establish (Hodges, 1995). In areas where water moves off the land abruptly with force and volume, the most dramatic disturbances occur along the edges of waterways where new banks are cut and fresh deposits of coarse sands create bars and deltas. Good examples of this occur in the foothills of large mountain ranges such as the coast ranges of the Cascades, the Sierra Nevadas of the Pacific Northwest, and the Andes of South America. Tree species that have been documented to rely on such violent disturbance regimes for their establishment include poplars, sycamores, and Sitka spruce of temperate realms (Yarie, 1993; Hodges 1995; Scott, Auble, and Freidman, 1997; Scott *et al*., 2012), and mahogany and Spanish cedar of tropical regions (Salo *et al*., 1986). However, in most places, water levels are often controlled more by hydroelectric and flood-control needs than by plans for silviculture. However, for the creative forester such measures may be appropriate and available.

Mechanical Treatments – Surface Scarification to Deep Plowing

One mechanical method of site preparation, **reduction of undesirable vegetation**, can be done by uprooting large woody plants, chopping up smaller plants, or plowing under grasses and other herbaceous growth. The objective of this step is to disrupt the roots of the undesirable plants enough to kill them or at the very least reduce their regrowth. Of course, mechanical equipment can be used simply to cut or break off the stems of woody plants, especially those that are incapable of sprouting. It might be possible to eliminate only the woody vegetation and leave any grasses or other low plants alone, especially if their competition is not likely to be significant and excludes more troublesome plants.

Practically all mechanical site preparation involves some **redistribution of dead vegetation**. This may range from concentrating uprooted trees into high windrows, to the gentle **scarification** of thin litter beneath otherwise undisturbed vegetation. With large debris, the objective is partly to remove obstacles to subsequent operations. It may also be desirable to hasten the destruction of debris. This can be done by pushing it into compact piles or working it into the mineral soil so it will rot more quickly. With the gentler kinds of treatment, there may be no objective other than **exposure of mineral soil**. For obtaining natural regeneration, this is usually all that is required and can be done with a root rake, either manually in small areas or with a tractor. Any method of mechanical site preparation exposes some of the mineral soil, often in the process of doing something more difficult.

If the site is subject to extremes of moisture conditions, activities occasionally include **reshaping** the soil surface. This usually is done by plowing or scraping to create low ridges in wet places or shallow trenches to collect water in dry areas.This is called **bedding and mounding**. Sometimes **smoothing** of the surface with harrows may facilitate machine planting or other future

activities. The more intense mechanical treatments tend to be restricted to preparation of sites for planting of tree plantations, agroforestry systems, and orchards. Most mechanical treatments are less extreme when the goal is to secure natural regeneration by exposure to mineral soil.

The equipment used and the cost for the work varies widely and most of it requires tractor-powered devices. The methods are ordered, starting with just crushing residual vegetation and ending with the complete removal of the original vegetation and turning of the soil.

Scarification to Prepare the Seedbed

Simple scarification designed merely to expose mineral soil can be done with light equipment. Single- or double-moldboard plows, including those designed for constructing fire lines, or special shaping devices can be used for furrowing or bedding. If the intention in many circumstances is to just expose the forest floor and mineral soil, then the simplest treatment is to move the debris around and redistribute it; this can often be done at the time of harvest with a logger, just using the logging equipment itself. For many forest types, this is sufficient to allow light-seeded species enough growing space to germinate. More purposeful scarification using a root rake can be done where more uniform open conditions are desired for pioneers. This kind of treatment will need to dispose of the slash in some way by piling, burning, chipping, or some combination of these.

Chopping and Crushing to Reduce Vegetative Competition and Improve Infiltration

Most site preparation is aimed chiefly at the destruction of competing vegetation. Plants of sapling size or smaller can be broken up and worked into the soil with heavy disk plows or rolling brush choppers (Fig. 7.5). It is often desirable to induce sprouting with an initial treatment and then follow it with a second treatment to kill the new, succulent sprouts before they form buds. The second treatment can be another mechanical one, or it can be prescribed burning or herbicide spraying.

Devices similar to large, rotary lawnmowers can be used to cut and shred small vegetation and woody debris before planting, but they do not eliminate sprouting vegetation. Bulldozers or similar devices (Fig. 7.6) can be used against vegetation of any size from small brush to large trees. However, they must be fitted with special toothed blades or root rakes (Fig. 7.7) if they are to be effective in uprooting anything without scraping away too much topsoil. Large areas of trees are sometimes uprooted by using powerful tractors that drag battleship anchor chains over the ground. The huge links of these chains pinch around the bases of the trees and remain engaged until the trees are pulled over. Ordinarily, pairs of tractors are used to drag one chain. The uprooted trees must then be pushed into windrows with bulldozers. This is an old practice of forest clearance for conversion to pasture in the West and is generally no longer practiced. Some of these techniques can be used in young precommercial stands that have burned and need to be replanted.

Mechanical site preparation of the kinds described is usually a preliminary to planting. If there has been any substantial overturning or upheaval of the mineral soil, it is necessary to delay planting for several months to allow the soil to settle. Otherwise, there is risk that many of the roots of the seedlings will be planted in air pockets and die of drought. The smoothing of areas with heavy harrows is often aimed chiefly at making it possible to plant with machines. Although the competing vegetation is greatly

Figure 7.5 Bulldozers with rolling drum choppers being used to destroy hardwood brush preparatory to planting pine on a dry, sandy site on the southeastern coastal plain. *Source:* Yale School of Forestry and Environmental Studies.

Figure 7.6 "K-G" blade. The sharpened blade is set at an angle so that it can be used to shear off the trees at or below the ground line; the upper bar pushes the trees over as they are being severed. The "stinger" at one end of the blade is used to split the stem of a large tree so that it can be cut off or pushed over in two passes of the machine. *Source:* Yale School of Forestry and Environmental Studies.

(a)

(b)

Figure 7.7 **(a)** A root rake attached to a bulldozer. The rake is designed to scarify the topsoil but not to remove it in soil preparation. *Source:* US Forest Service. **(b)** A steel chain dragged behind a skidder used to scarify soil surface for jack pine seed germination in Wisconsin. *Source:* M. Ferrucci. Reproduced with permission of M. Ferrucci.

reduced by such drastic treatment, some sprouting rootstocks are usually left in the soil. These techniques are often employed for getting rid of the sparse, small hardwoods in pine stand understories after a pine harvest. They are also advantages in replacing degraded hardwood stands with pines because well-established hardwood stands are almost impossible to eliminate by prescribed burning. The timing of all of these site-preparation operations needs to be done to accommodate the window of time to plant or facilitate natural regeneration.

Bedding and Mounding to Improve Drainage

Bedding is the mounding-up of low ridges or "beds" on flat, poorly drained land such as those common on the lower coastal plain of the southeastern United States (Fig. 7.8). It is also used widely in Scotland, Ireland, and parts of Scandinavia and northern Canada (Rothwell, Woodward, and Rivard, 1993; Paavilainen and Paivanen, 1995). It has the effect of increasing the volume of soil that is sufficiently well supplied with oxygen and water to lengthen the period of physiological availability of water. It also incorporates organic matter into the mineral soil and increases decomposition and mineralization. Both of these effects speed the growth of new stands at least until the stand closes, although some slight advantage might theoretically persist for longer. Windthrow problems sometimes result from trees developing roots only along the beds with Sitka spruce in Scotland and Ireland (Paavilainen and Paivanen, 1995). Sometimes bedding is extended by force of habit to drier sites where it may do harm by planting in areas that are already dry (Aust and Blinn, 2004).

In other regions with organic soils such as the upper peninsula of Michigan or the peat systems of northern Finland, **mounding** is commonly practiced. Machinery recreates what would look like an artificial pit-and-mound topography. Such topography on wetland sites is common, and is natural for cedar swamps (*Chamaecyparis* spp., *Thuja* spp.) because such forests are shallow rooted and predisposed to windthrow. In this circumstance, seedlings are planted on the sides of the mounds for better drainage. Planting on the mound top is avoided because of susceptibility to windthrow.

Plowing and Deep Plowing to Break Up Surface and Subsurface Soil Compaction

Under extreme cases, the **loosening of compacted soils** may be done by plowing. Ordinarily, the natural soil organisms of the forest keep the soil in a more porous

Figure 7.8 A flat, poorly drained site in North Carolina bedded in preparation for planting loblolly pine. The raised beds or berms, on which the trees are to be planted, were cast up with a special plow and shaping device to provide ridges of aerated soil in which the roots can start their expansion. *Source:* Mark S. Ashton.

and penetrable state than could be accomplished by mechanical churning. However, mechanical loosening does help if the hooves of herbivores or the weight of heavy machinery on former agricultural lands have made the soil very compact. Also, the areas used for loading logs can be a particular problem.

Very deep plowing (also called **ripping** or subsoiling) is sometimes used to break up subsurface hardpans that have been formed either by natural processes or as the result of poor use of some sensitive soils for grazing or agriculture. In certain places it can actually be used to recharge groundwaters in arid grazed lands (Scanlon *et al.*, 2008). However, this sort of plowing is most common in very humid climates, such as those in parts of Scotland, Wales, and Ireland. Sphagnum bogs and hardpans can form, even on hillsides, because of the leaching associated with the podzolization process that can occur from a thousand years of deforestation and repeated burning fields for sheep and game (Morgan, Campbell, and Malcolm, 1992; Sutton, 1993). If the accumulation of oxygen-deficient water or merely resistance to root penetration restricts rooting depth, the breaking of impediments to downward movement of water helps growth. Contour plowing to avoid erosion on coastal sites in the southern US is a routine form of site preparation for plantations.

On very dry sites, plowing may improve the survival and early growth of planted trees to plow out furrows or to construct contour terraces and depressions in ways that will collect water and uproot or bury competing vegetation. In some arid regions, it is impossible to get trees to start without artificial means of creating localized microenvironments where the soil retains moisture. Contour terraces have been successfully used in the northern Rocky Mountains, although there has been some objection to the artificial appearance that it confers on the terrain. Creating terraced contours by deep plowing is a common practice in Israel and elsewhere in the Middle East (Bouman, 2007). The creation of circular depressions for seedlings planted in the center is another similar practice in dry parts of the African Sahel (Evans, 1984).

Limitations of Mechanical Treatments

In all treatments of this sort, the horizontal movement of organic materials and topsoil should be avoided as much as possible. The churning or overturning of these materials in place is distinctly preferable to any sort of scraping action (Fox, 2000).

Much of the nutrient capital of the forest is usually tied up in the litter and upper layers of the mineral soil (Binkley, 1986). Most of the forest system's power to resist erosion and protect water quality resides in the protective covering of the forest floor and the infiltrative capacity of the uppermost layer of mineral soil. No silvicultural practice can impair the productive capacity of the forest or damage watersheds more than scraping off the surface soil. This is especially true if the nutrients are moved farther sideways than the true extent of the tree roots that might bring them back. Bulldozers and root rakes should be regarded as instruments with more potentialities for damage than fire, herbicide, or other forestry tools (Fox, 2000).

The practice of windrowing uprooted material is an especially questionable practice (Morris, Pritchett, and Swindel, 1983; Binkley, 1986). It is impossible to do this without moving not only nutrients but also some mineral soil. This effect is often made apparent by the fact that planted trees (or weedy vegetation) grow fast in the windrows, whereas the other trees may be stunted and chlorotic for a time (Fig. 7.9). The windrows sometimes waste growing space. Closer utilization may reduce the use of the practice, but it is much better for the soil and site productivity to employ rolling brush cutters, plows, or other devices that work material into the soil without moving it sideways. It is ironic that silvicultural efforts to emulate the clean cultivation of agriculture have developed at the same time that efforts have been made to use herbicides for "minimum-till" agriculture. Clean-cultivation agriculture is an inherently depletive process. Most silviculture is not, because it defends the soil against erosion by conserving rather than squandering soil organic matter. Studies have been done elaborating on this work in the southeastern United States (Haywood, 1994), and the Pacific Northwest (Minore and Weatherly, 1990; Haeussler *et al.*, 1999; Boateng *et al.*, 2006). These studies demonstrate that the best treatments rely on the broadcast distribution of slash without piling it or turning over the soil.

Light scarification and the plowing of shallow furrows are usually cheap, but measures that require powerful machinery can be very costly. Windrowing is one of the most expensive operations. If the investment in equipment is high, the cost may vary considerably depending on how the depreciation of the machines is treated in the accounting. The use of machinery should therefore be the result of thoughtful prescription and not a matter of unquestioned standard operating procedure. In certain regions where it has been applied under the wrong site circumstances, productivity has declined over successive rotations. For instance, examples have been recorded on heavy clay soils that are sensitive to compaction, or on sandy nutrient poor soils of the southern US (Ruark *et al.*, 1991; Bechtold, Ruark, and Lloyd, 1991; Haywood, Tiarks, and Shoulders, 1990), and on certain fragile, nutrient-poor soils of Australia (Squire *et al.*, 1985). It is not a common practice anymore in the US because of its proneness to abuse, but it can be found elsewhere. The latest example of poor planning and unsustainable practice is large-scale forest clearance for ranching, using windrows on poor clay oxisols of the Amazon.

(a)

(b)

Figure 7.9 Windrowing of stumps and logging debris and the effect that the associated scraping action can have in moving nutrients sideways. Both pictures show site preparation for planting on the Atlantic coastal plain in North Carolina. **(a)** An old photograph showing a very thorough job of concentrating the debris in a tight windrow. **(b)** Tall loblolly pines growing in the nutrient concentration of such a windrow to the left but with stunted and somewhat chlorotic seedlings on the center (with the survey rod) in the zone from which materials had been pushed with a root rake. Windrowing is rarely if ever practiced in the US, given its potential degrading effects on top soil. *Source:* **(a, b)** Mark S. Ashton.

Site Protection of Surface Soils

Site protection as the second category of site treatments can largely be characterized as not necessary for most methods of planting and natural regeneration. Almost all of this chapter has focused on manipulative techniques for preparing the site for establishing various kinds of vegetation or for excluding unwanted vegetation. In many other circumstances, rather than preparing a site by exposing mineral soil or by excluding unwanted vegetation, the site must be protected from erosive forces of climate or land use. Sites where protection is required are often prone to continuous or frequent disturbances that prevent vegetation establishment and soil stabilization. Examples can be found in nature along coasts, such as in dune systems, or along the banks of fast-flowing streams. Overuse of land from chronic grazing or continuous cultivation of steep slopes are also examples of sites that can become unstable and are prone to erosion. Under more intensive agricultural or agroforestry systems that undergo chronic levels of annual or superannual disturbance from cultivation, site-protection treatments are very important, particularly where agroforestry and/or agricultural tillage is being promoted on fragile and marginal soils that might be relatively infertile or erodable, such as on steep slopes or flood plains. In such circumstances, promoting a vegetated low groundcover or mulch that can protect the surface soil moisture, fertility, and structure is integral to sustaining the site's productivity. Such systems of treatment can be perennially maintained in orchards or tree–agricultural crop systems, or they can be used temporally by season as a fallow cover. Under circumstances where soils are very unstable, it may be important to construct physical structures, such as terracing and contouring, rather than use of vegetative cover.

Mulches and Groundcovers

In most circumstances when considering the protection of the soil surface of a new regenerating stand, nature has an inherent number of protective barriers that a manager will have to actively fight against if so desired. Nature's protective barriers include the litter layer, dispersed slash, course woody debris, and existing vegetation that includes either advanced tree regeneration, an existing protective canopy of trees from the original stand, or new colonizing vegetation that is often annual and/or herbaceous. For most forests where advance regeneration is required for a new stand, such protection is thus already provided.

For plantations, and where growing space for tree crops is carefully controlled, nature's protective barriers are usually substituted by managers in their efforts to completely control the composition and structure of the vegetation on the site. To ensure site protection in these circumstances, but at the same time control competition with planted seedlings, groundcovers and mulches are often used. Groundcovers are low statured, prostrate herbs and ground vines that, through their leafy matt, reduce surface soil temperatures and retain surface soil moisture. Many also fix nitrogen, enriching soil that if severly eroded or disturbed is often the one nutrient most lacking (legumes – *Pueraria* spp., *Desmodium* spp., *Trifolium* spp.) (Alley *et al.*, 1999; Delate *et al.*, 2005) (Fig. 7.10). Selecting an appropriate groundcover can reduce the competition of the planted seedling with colonizing opportunistic competitors (Alley *et al.*, 1999).

Figure 7.10 Ground cover establishment in a newly established rubber plantation. *Source:* Mark S. Ashton.

Alternatives to groundcovers are organic mulches (often by-products from site treatments themselves) and chips and bark mulch, or other forms such as hay and plastic, all of which have been shown to improve growth and establishment of planted tree seedlings (Adams, 1997).

Last and most importantly, mulches and groundcovers are one of several solutions that, taken together, can be used to stabilize and restore soils undergoing severe erosional processes (Pimentel *et al.*, 1995).

Contouring and Terracing

There are many protective techniques that can be broadly defined as **contouring**. All contouring involves constructing physical or vegetative obstructions that are arranged parallel to the contour of the slope or disturbance-prone edge, and serve to stabilize earth movement and soil erosion (Fig. 7.11). Examples of contouring include hedgerows, windbreaks, stonewalls, rip-rap, ditches that collect and channel water away from sensitive sites, and ground covers (deep-rooted grasses) aligned in rows. The best examples of this used currently in North America are in the midwest (Gillespie, Miller, and Johnson, 1995), but such systems are widely used throughout the world where agriculture has been pushed to the most marginal steep-sloped soils because of necessity (Boubari and Morgan, 1999; Angima *et al.*, 2002). For most applications in silviculture, contouring is used to temporarily stabilize a site and promote succession. However, where silvicultural techniques are used to arrest successional processes, as in the case of many agroforestry systems that promote permanent agriculture, contouring may be a more permanent part of site protection. This is particularly the case where crop cultivation or animal grazing is, at least in some form, present continuously on the land. Investments in contouring can be taken to extremes with the construction of permanent stone or earthen **terraces**, some of which have sustained agricultural productivity for thousands of years. Such terraces have been designed to control water by capturing excess surface runoff, carrying it through stone-armoured ditches, and then delivering it to temporary storage in bioswales. Other studies have found such systems can be designed for the reverse; in other words, to act as a trap and prolong moisture storage in localized areas where trees have been planted, which is particularly useful in arid climates (Ternan *et al.*, 1996; Fitzjohn, Ternan, and Williams, 1998). On certain sites, the ground surface may be completely protected by either vegetative covers (often nitrogen-fixing legumes), organic mulches (hay, wood chips), or synthetic mats.

Site Improvement, Conversion and Restoration

The last site-treatment category is one which should be rarely practiced. In North America, treatments that would fall into this category are now often part of site-restoration plans and activities. However, in other parts of the world they are often associated with site-conversion treatments where forests are being predominantly transformed into agricultural plantations. Such examples are the clearance and drainage of peat swamp forest for oil palm plantations in Indonesia and Malaysia, or the clearance of dry tropical forest in Brazil for irrigated soybeans. Such land conversions usually spell trouble, and generally violate one of the core principles in ecologically based silviculture. Avoiding circumstances of trying to change the site to fit the desired crop, it is more desirable to select an appropriate crop that fits the site.

However, the three core treatments – fertilization, drainage, and irrigation – are intensive manipulations of the soil that are aimed more at converting, improving, or restoring site quality than at preparing for regeneration. The proper conduct of these treatments depends so heavily on knowledge of the complex chemical properties of soils and their moisture relationships, that it is logical to refer to works on forest soils and other accounts, such as those of Ballard and Gessel (1983) and Binkley (1986) for more complete information. Land conversion for drained or irrigated crop cultivation is rife with failures both in North America and in other parts of the world (e.g., the salinization of the Central Valley, CA; drainage of the lower Missisippi; the salinization of the Murray–Darling, Australia).

Fertilization

The use of fertilization in forestry produces the least site disturbance in the three site treatments described in this category. Many silvicultural uses are for establishing planted seedlings in reforestation or in newly established plantations (Jacobs *et al.*, 2004; Dumroese *et al.*, 2005; Jacobs, Salifu, and Seifert, 2005). Fertilization is also used for larger trees and in repeated applications. Most forest soils do not provide an optimum supply of the nutrient elements essential for growth of trees. Some sites just have inherently low natural fertility, but on other sites, deficiencies may exist because of improper land management in the past. The nutrient elements most likely to be deficient are **nitrogen**, **phosphorus**, and **potassium** (the **NPK** elements of most fertilizers) (Binkley 1986). It is often possible to make forest trees grow faster and better by increasing the supply of nitrogen (N). The most common nitrogen fertilizers used in forestry are urea compounds that produce ammonium-N, which can be absorbed in the cation-exchange capacity of the soil and are easily taken up by plants. Urea formaldehyde compounds have the advantage of releasing the ammonium-N slowly. Nitrate-N compounds can also be used, but it is more easily lost from the soil by leaching. Diammonium phosphate (NP) and urea are the most common forms of fertilizers used in the southern US. Nitrogen in the forest

Figure 7.11 Examples of contouring and terracing on steep slopes. **(a)** Crop terraces in Guizhou, China, used to structurally prevent surface erosion and earth slips. *Source*: Mark S. Ashton. **(b)** Hedgerows in southern England, UK, to confine livestock and mitigate soil erosion when the field is cultivated. *Source:* Mark S. Ashton. **(c)** Contour tillage and the use of groundcovers to prevent surface erosion and promote infiltration. *Source:* J. Sohm. Reproduced with permission from Shutterstock. **(d)** Ditching in a tea plantation to prevent surface erosion and to guide excess water immediately off site. *Source:* Mark S. Ashton.

system is constantly moving to and from the atmosphere or being lost to moving soil water. It can also become unavailable to higher plants by being captured by decomposing organisms in the soil or by being locked up in undecomposed organic matter. This often happens where the soil climate is unfavorable to decomposition. It is sometimes possible to remedy nitrogen deficiencies by stimulating the symbiotic and non-symbiotic nitrogen-fixing organisms. Fertilization with other elements sometimes stimulates the nitrogen-fixers, such as legumes, alders, and other plants that support symbiotic nitrogen-fixing bacteria.

The cost of artificial fixation of nitrogen for fertilizer in terms of both money and energy is high. The effects of a given application are limited to several years, so repeated applications may be necessary. Fertilization with nitrogen compounds alone has become moderately common in the humid parts of the Pacific Northwest (Miller and Fight, 1979) and in other forest areas where growing conditions are good, and soils and weathering processes are young. Nitrogen may be the most important limitation for timber plantations (Binkley 1986). However, it is important in some situations to balance the proportions of the fertilizer compounds (Mika and Moore, 1991). This situation occurs most frequently when municipal wastewater or biosolids are being disposed in forests. This is a very useful way to increase tree growth and dispose of waste materials. However, with these large amounts of nitrogen, a senstivity in the balance of nitrogen and potassium arises. The imbalance of these two elements has caused growth declines in Douglas-fir and red pine. However, white pine, oak, maple, and birch had no declines in growth. Thus, it may be necessary to apply potassium fertilizer in combination with N-fertilizers to avoid imbalances in some species.

Phosphorus deficiencies remediable by fertilization are common on poorly drained soils. In these and most other cases of phosphorus deficiency, the problem is that the acid condition of the soil or other factors cause too much phosphorus to be tied up in unavailable form in compounds with iron and aluminum (Binkley, 1986). Phosphorus can be applied as ground phosphate rock or in more concentrated form. These do not consume much energy in manufacture. However, phosphorus is usually applied as diammonium phosphate. Single applications have long-lasting effects (Fox *et al.*, 2007), and potentially carry over effects into the next rotation (Subedi *et al.*, 2014). Highly weathered clay-based soils of humid regions such as the southeastern US are often phosphorus deficient. The amounts of nitrogen and phosphorus available to plants must be well balanced. What might otherwise be the right amount of one can make a deficiency of the other more acute or even harmful. If a tree has more phosphorus to form the energy-transfer machinery of photosynthesis, for example, it also needs more nitrogen to build the protein components of this machinery.

If there is opportunity for good nutrient recycling, single applications of potassium fertilizer in the forest seem to be sufficient for very long periods. Potassium is a very soluble and mobile compound, so it is easily lost by leaching. Deficiencies have been encountered on easily leached sandy soils previously subjected to highly extractive kinds of agricultural crop removal in New York State (Leaf and Leonard, 1973).

Few cases in forestry show that fertilization with other elements has had actual benefit. It is rather surprising that there is little evidence of improvements from adding calcium, magnesium, or manganese. In the US south, slash pine showed deficiencies in manganese (Jokela *et al.*, 1991; Fox, Jokela, and Allen, 2007) and copper (Vogel and Jokela, 2011). However, there are some unusual deficiencies such as areas in Norway with both fertile soils and peatlands, but with poor tree growth. It has now been determined that boron (B) is the element that was deficient. The application has solved the problem. On the other side of the world, deficiencies of trace elements such as zinc, molybdenum, boron, cobalt, and copper are known mostly from a few districts in Australia (Evans, 1984). Australia is an ancient and strongly leached continent where deficiencies of phosphorus and other elements have caused forest fertilization to be much more remarkably successful than in most parts of the world.

Forest fertilization is normally done from the air. It is very important to avoid fertilizing the forest waters so as to avoid contributing to eutrophication. The materials to be spread are heavy enough that it helps to minimize flying distances. Such practices are now really restricted to intensive plantation systems. Interestingly, nitrogen deposition in regions downwind of pollution, such as northeast US and the Maritime Provinces of Canada, are now altering the nitrogen status of such forests (Aber *et al.*, 2003). It is debateable as to whether they are acting as a fertilizer. However, there is also some evidence that air pollutants (nitrates and sulfates) have promoted the acidification of soils, that are already acid prone, such as the granitic soils of northern hardwood forests of the northeastern US. Under these circumstances, cations such as calcium have been disproportionately leached into waterways, leaving these soils calcium deficient and more sensitive to site-preparation treatments.

In most cases, it is important to manage stand density when applying fertilizer, and to apply it only when it is actually limiting. Sometimes it is best to restrict forest fertilization to the latter part of the rotation. A given amount of fertilizer seems to produce about the same amount of wood regardless of tree size, and a given cubic volume put on large trees is worth more than the same volume put on small trees. Furthermore, the supply of available nutrients is

generally greatest just after the destructive events associated with regeneration (Bormann and Likens, 1979). Deficiencies are most likely to set in after the stands have filled all the growing space and many more nutrients are getting tied up in living and dead organic materials on the site (Harding and Jokela, 1994). Fertilization is done at the time of planting or regeneration only if the deficiencies are very serious, as on recently drained organic soils (Taylor, 1991). Sometimes fertilization of young stands favors the competing vegetation more than the trees. In some examples, fertilization has changed the composition of the groundstory vegetation (Prescott *et al.*, 1993) and in other cases it is not needed, or it induces harmful imbalances between nutrient elements.

Past research has revealed that the use of organic biostimulants as a stress vitamin can stimulate plant growth and provide optimum yields with up to 50% reduction in fertilizer use. Organic biostimulant research has shown increased efficiency of nutrient uptake, and has demonstrated that increased vigor from supplemental vitamins has enhanced synthesis of defensive polyphenols that make treated plants less susceptible to herbivory (Russo and Berlyn, 1990, 1992; Richardson *et al.*, 2004). These compounds are now commonly applied to street-tree plantings.

Drainage

There are large areas of forested wetlands throughout the world (called swamps, bogs, peat bogs, muskegs, and other terms) that could be drained to increase forest growth. The stagnant oxygen-deficient water can be almost like arid deserts with respect to plant growth (Kozlowski, 1984). The decomposing organisms break down the organic matter, robbing the water of the oxygen that the roots of higher plants must have to function. Therefore, trees growing in bogs can extend their roots downward only a few inches (centimeters), and the strata below are as impervious to roots as rock would be. This situation prevails only where water is stagnant or slow moving. Sites along freely flowing streams can seem equally wet but often are biologically the most productive of any of a given locality; in such places, the water is well aerated with freely available oxygen. At least it can be said that many tree species seem adapted to this phenomenon. Many species of literally dry sites (such as deep sands or thin soils) are also found in physiologically dry swamps. Some of the examples include black gum, red maple, black spruce, and some species of pine. The most common indicators of oxygen-deficient water, the world over, are sphagnum mosses. These mosses not only indicate bogs, but in very humid climates, such as in parts of the British Isles, they can even create bogs on hillsides because of their very large water-holding capacity.

Some of the previously described methods of using plows for bedding or puncturing hardpans accomplish some drainage, especially on sloping ground. However, water is viscous enough that such measures do not really move much off of flat terrain. This requires ditches or canals as well as enough difference in elevation to provide places to which water can flow (Paavilainen and Paivanen, 1995). In the US, the drainage of wetlands is now illegal, but lands that were drained prior to the Wetlands Act can be maintained (National Environmental Policy Act, 1969; Clean Water Act, 1972).

The most common method starts with the use of backhoes or draglines to dig parallel primary canals, and the fill that is placed between them becomes an access road (Fig. 7.12). Secondary ditches are constructed to lead to the primary ditches, usually at right angles and at

Figure 7.12 Drainage canal with water-regulation device, designed to move water off a very flat site in North Carolina. The road is made of soil dug from the ditches on either side of it. The canal is adjacent to the bedded area shown in Fig. 7.8. *Source:* Yale School of Forestry and Environmental Studies.

intervals of about 100 ft (30 m). In the process of site preparation for planting, the sites are often bedded with plows so that the trees can be started on low, well-drained ridges. Unless they have been enriched by nutrients flowing off adjacent uplands, the organic soils will be deficient in nutrients, especially phosphorus and nitrogen. Fertilization is commonly needed, and it usually takes much local experimentation to determine which fertilizers and how much of each.

It must be anticipated that drainage will cause the newly aerated peat to decompose in such a manner that the surface will sink. Sometimes this proceeds to the point where the ditches have to be deepened. If there is no longer enough difference in elevation for the water to move, the whole effort is defeated. The worst situation occurs on lands that have a thin layer of light freshwater over dense salty water. The saltwater rises as the freshwater moves to the top while the surface subsides. On the other hand, if a treeless area is drained and afforested, the trees can transpire enough water to improve their own growth by removing excess water.

The largest forest drainage projects are those of peat bogs that have formed in former lakes in glaciated lands in Finland, Scandinavia, and Russia (Fig. 7.13). The techniques, which usually have to include fertilization of the sterile peats, are highly developed and based on detailed classifications of the different kinds of wet sites. In these countries, there is growing sentiment that drainage of peat bogs may have gone too far, creating concerns about landscape diversity and plant and animal habitats. Thus far, few attempts have been made to drain similar bogs in Canada and the northern United States. Most North American forest drainage was on the flat coastal plain of the southeastern United States. The most successful efforts have been with very flat but somewhat elevated areas distant from major rivers. These are wet mostly because of the flatness of the land and have comparatively thin layers of peat. If the drainage ways are kept open and phosphorus deficiencies are remedied, the drainage of these soils makes them so well supplied with aerated water that they become highly productive (McKee *et al.*, 1984; Binkley 1986). The drainage of depressions in this region is more difficult, and the results vary. Attempts to drain forest areas that are almost at sea level and underlain by saltwater have been costly failures (Haywood, Tiarks, and Shoulders, 1990).

Irrigation

Except for seed orchards, nurseries, and other sites of very intensive tree culture, little use is made of irrigation in forestry for most moist regions where trees grow prolifically. Irrigation water is usually more valuable for agricultural use and for fruit and nut orchards, particularly where rainfall is low but the soils are fertile (i.e., the central valley of California). Care must be taken on these intensively managed sites to avoid salinization. For forestry, there are only a few places in the world where hybrid poplars and other species of alluvial flood plains are grown with supplemental irrigation water. The most common ways of increasing the water supply of forest

(a)

(b)

Figure 7.13 **(a)** Scots pine stands on drained peatland in Finland. The trees were absent or badly stunted before the drainage started 50 years ago. The surface has subsided about a meter because of decomposition from the aeration of the drained peat. *Source:* Yale School of Forestry and Environmental Studies. **(b)** Bedding and mounding site preparation to improve microsite drainage for planting northern white cedar in the Upper Peninsula, Michigan. *Source:* Mark S. Ashton.

trees are those methods of reshaping the ground surface to concentrate surface runoff water on the roots of planted trees that were mentioned earlier in connection with mechanical site preparation.

The most notable use in forestry is for the purposes of intensive poplar cultivation in the interior west and restoration, particularly in relation to reclamation of surface mine spoils (Larson, Patel, and Vimmerstedt, 1995; Messina and Duncan, 1993; Vogel, 1981). The effect of timber cutting and grazing for several millennia have completely degraded sites in arid areas. Irrigation can be used in promoting the establishment of a new forest or woodland. Once the forest ecosystem is functioning, irrigation can taper off. Some of the most advanced mechanical methods of accentuating water capture and also the use of drip irrigation (tubes that supply constant drips of water at the base of each planted tree) have therefore been used to combat these processes of desertification in the Middle East (especially Israel), the African Sahel (FAO, 1977), central China, Pakistan, and central India (Ffolliot *et al*., 1994). Drip irrigation is also widely used in poplar plantations that are intensively managed for biomass production on dry but fertile soils of flood plains of the inland west (Oregon, Washington).

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Part 3A

Natural Regeneration Methods

Regenerating stands of trees by judicious use of site treatments in combination with with tree canopy spacing and species selection to promote desired tree species assemblages and age class distributions.

8

Natural Regeneration: The Clearcutting Method

Introduction

The **clearcut method** deals with forest stands that originate as a single age class that have been established following a complete harvest and site treatment that creates a lethal disturbance. This is defined in silviculture as a **clearcut**. A variation in the clearcut method is called clearcut with reserves, which retains individual trees, intact patches, and other forest structures within a clearcut stand (see Chapter 11 for a more detailed description). The clearcut method is also called **true clearcutting**.

Single-species, uniform-sized, even-aged stands regenerated by **true clearcutting** are the kind that are best understood and simplest to manage. They start with growing spaces that are almost completely free of trees and most other potentially competing vegetation. Clearcutting mimics the most lethal of natural disturbance regimes that can occur to the site (e.g., very hot forest fires). Site treatments that accompany true clearcutting are some of the most intensive manipulations to the groundstory to both eradicate existing vegetation, and to prepare the ground surface as a suitable seedbed and microenvironment for new regeneration. Seeds germinate and seedlings establish *after* the regenerative disturbance, usually within a very short period of years, and the new trees all grow up together in a single cohort. The development of the stand is so uniform that the even-aged yield tables that are discussed in connection with thinning, can be used to predict their development. Species that regenerate by this mode are pioneers that are very shade-intolerant, small-seeded, fast-growing, and early- to mid-successional species.

Pure even-aged stands usually persist only where the site conditions are so difficult that only one or two tree species can endure the environmental extremes of sites that are too dry, too wet, too cold, or too hot. Regional examples where forest types are pre-adapted to lethal disturbances, and where true clearcutting might recreate such disturbance can be found in the Intermountain West, the pinelands of the southeastern US, and the interior fire-prone boreal of Canada (Table 8.1). On better sites, severe disturbance can create conditions during the next establishment period that may be favorable to only one hardy species. On other sites, some pest or damaging agent may allow only one species to persist. It is also possible to create such stands by silvicultural treatment, although it is not necessarily easy to maintain them. On fertile moist sites in climates that are more moderate, true clearcutting may open the way for invasions by jungles of mixed species, often including invasive species that are virtually impossible to control.

Creating the necessary conditions for establishment requires intensive site-preparation measures such as those described in Chapter 7, and good knowledge that there is an adequate and abundant seed source of desired pioneers that can colonize the new open area quickly and completely.

The Protocol

The clearcut regeneration method involves only one cut.

Clearcutting: this cut removes the entire canopy of the stand, leaving maximum growing space. Site preparation is usually associated with the harvest, in order to create conditions for newly established seed germination and seedling development.

Misuse of the Term Clearcutting

It might seem that the word “clearcut” would be completely understood, but it is used in ways that have very different meanings to different people. As a technical term of silviculture, clearcutting refers to treatments in which virtually all trees and other vegetation are removed, and almost all of the growing space becomes available for new plants. Timber harvesting alone is usually not sufficient to achieve a complete removal of vegetation; that is one of the main roles of the site-preparation measures that were described in Chapter 7. If this kind of clearcutting is meant, it should be referred to as: **true clearcutting**, **the clearcut method**, **silvicultural clearcutting**, or **complete clearcutting**; sometimes the term **clean cutting** is used, from the British usage.

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

Table 8.1 Examples of the natural disturbance regimes of forest types and the species that can be regenerated by true clearcutting in North America.

Region and species/ forest type	Disturbance regime and return interval
Interior boreal	
Jack pine	Fire return intervals for jack pine vary between 5–50 years. Severe stand-replacing fires are on the better soils with longer return intervals. The poorest soils have frequent intervals promoting a pine barren. The cones exhibit serotiny and require fire for release of seed and germination on mineral soils
Black spruce	Like jack pine, the species spruce regenerates from cone-stored seed after a fire. However, spruce is restricted to acidic organic bogs. Nearly all stands are replaced by fire at 50- to 150-year intervals. Areas that have burned create a complex mosaic with unburned areas. Periodic extreme summer droughts promote larger and more lethal fire events
Pacific Northwest	
Douglas-fir	Douglas-fir with its thick bark is the most fire-hardy tree of the Pacific Northwest where it co-exists with a group of more shade-tolerant and mesic-loving species. Douglas-firs that survive catastrophic stand-replacing fires that can occur every 500–1000 years germinate well on mineral soil. Seeds require a good mast year and a nearby seed source for quick establishment and stocking
Red alder	This wind-dispersed prolific seeder regenerates on moist sites, especially along riparian zones. It is a strong competitor of Douglas-fir in such areas. It regenerates from riparian flooding events on new sandy deposits or after fires that expose new growing space and mineral soil
Intermountain	
Lodgepole pine	The accumulation of fuels, insects, and climate, all interact to regenerate lodgepole pine in stand-replacing fires. However, these fires can form a mosaic; only in parts of its range does it exhibit serotiny and an ability to regenerate after hot fires. Lodgepole pine regenerates in monodominant stands at intervals of about 80–100 years. Stands can vary in stocking from open grown to very dense
Engelmann spruce/ subalpine fir	Both subalpine fir and Engelmann spruce are fire-sensitive, long-lived species at high elevation, easily killed in catastrophic wildfires that occur about every 150–400 years. These fires burn unevenly with pockets of trees surviving and serving as a seed source. Germinants require mineral soil but can take many years to establish within thick herbaceous vegetation that erupts after a fire
Middle west	
Eastern cottonwood	The shade-intolerant cottonwood, with wind- or water-dispersed seeds, colonizes new floodplains, deltas, and sandbars after severe flooding events of large river systems
Gulf Coast/southeast coastal plain	
Slash pine/longleaf pine	Mature slash and longleaf pine are fire resistant. Fire return intervals are 5–30 years with groundstory burns, and are generally not stand replacing. Seed is produced during mast years and is dispersed effectively over ~300 ft (100 m) from a parent tree. Clearcutting in small areas can be effectively done, but seed-tree and other two- to three-aged (multi-aged) methods are more reflective of the actual regeneration cycle
Loblolly pine/shortleaf pine	Loblolly and shortleaf are less fire resistant than slash or longleaf but have similar attributes. Low-severity spring burns that expose mineral soil before seedfall is the most satisfactory way of regenerating loblolly. In a large part of its range, it is the most shade-intolerant and fire-hardy species compared with its more mesic-loving shade-tolerant hardwood associates
Northern hardwood	
Paper birch	Paper birch is a prolific producer of light-weight, wind-dispersed seed that requires mineral soil to colonize stand-replacing disturbances such as fire and landslides
Pin cherry/black cherry	Many cherry species regenerate after stand-replacing disturbances from the soil seed bank. Both pin and black cherry are shade-intolerants, relative to their associates (sugar maple/beech). Fire return intervals are long (500–1000 years) and are stand replacing, greatly favoring cherry from the seed bank to the complete exclusion of other species, which are all fire sensitive

Source: Mark S. Ashton.

The main problem with the term clearcutting is that it is often used to describe logging operations in which only the merchantable trees are cut. These operations are often called a **commercial clearcut**. The problem arises when these kinds of logging operations are simply called "clearcutting". They have no connection to the establishment of a new regenerating stand. Instead, they are linked only to commercial exploitation of the standing timber. However, the logging industry will likely continue to use the term for their operations. The term **true clearcutting** should be used when there may be conflicting interpretations of these terms.

There are two situations where silvicultural methods appear to be clearcutting, but are not. First, the simple coppice method (see Chapter 12) depends on vegetative sprouting, but the degree of removal of the old stand very much resembles clearcutting. The difference is that the roots and stems are left alive as the source of vegetative sprouts for the next coppice stand.

Second, there are situations where mature forest stands grow above advance-growth seedlings and saplings. Removing the overstory would appear to be a clearcut method, but the regeneration is left to grow. The use of the term **one-cut shelterwood** (discussed in Chapter 10) has the virtue of focusing attention on the source of the regeneration, and is the more appropriate term to use if keeping to the proper silvicultural terminology of this book.

Regeneration of Pure Stands from Natural Seeding

True clearcutting exposes the site so much that it is compatible with natural (or artificial) seeding, only when the species are capable of enduring full exposure to mineral soil and sun. Thus, it is not suitable for certain shade-tolerant/exposure-intolerant species unless they are planted (and sometimes not even then). However, this attribute of clearcutting can be of some advantage if the goal is to encourage species of early-successional status and discourage seed regeneration of shade-tolerant species that happen to be undesirable.

The prospect of success with natural regeneration after clearcutting, and the ways of securing it, vary widely depending on the source and means of dispersal of the seeds. These distinctions are so important that each will be considered separately here.

Clearcutting with Seeding from Adjacent Stands

Sometimes it is possible to clearcut a stand and depend on the seeds that are dispersed from a nearby untreated stand to provide the regeneration. With such an approach, the type of dispersal is all-important. In the temperate zone, the pioneer species that are best adapted to this kind of silviculture are disseminated by wind. In the tropics, where it is less windy, small birds and bats may play a more important role, but there are still a number of wind-dispersed pioneer tree species such as Honduran mahogany. There are even species of river flood-plains, such as the tupelo gums of the bottomlands of the southeast, that can be regenerated after clearcutting by floating seeds.

Wind, water, and animals can carry a few seeds over very long distances. However, in regenerating forests, it is usually necessary to remember that the density of seeds deposited on a unit of ground surface varies inversely as some power of the distance from the source. The rest of this discussion about dispersal of seed into clearcut areas involves wind, but some of the same ideas may apply to other types of dissemination, and examples will be provided of other dispersal modes.

Wind-dispersed seeds usually have wings, and moving air is usually turbulent enough that some seeds are lifted aloft rather than dropping only downward after being released from the cones or fruits. Where surrounding trees are the only source of seed, the clearcut area must be sufficiently small (usually long and narrow) to allow for adequate dissemination to all points. Safe widths for clearings to be stocked by wind-disseminated seed can range from one to six times the height of the adjacent timber from which seed will be dispersed, and depending on the size and weights of the various species. The normal direction of the prevailing wind during the season of seed dispersal should be known, and the clearing should be located so that its long axis is perpendicular to this direction. Unless the clearcut area is very narrow, the distribution of regeneration is likely to be uneven. Models demonstrate that to predict where wind-dispersed seeds will land, it is important to know the parent tree source in the adjacent forest, the prevailing winds at time of seed dispersal, and the seed mass. Knowing these factors, the great majority of seed is dispersed no further than a few tree heights from the edge of the adjacent forest (Greene and Johnson, 1996) (Fig. 8.1).

Most dissemination occurs during dry, sunny weather when the winds are brisk and gusty. The most effective winds are frequently those that blow the dry interior regions of continents, but they are not necessarily of the same direction as the prevailing winds. In terrain with rugged topography, it is best to have the long axis of the clearcut opening run perpendicular to the contour lines, because the winds responsible for dispersal of seeds are usually altered in direction so that they blow up or down valleys. An example would be the seed dispersal of western larch on the midslopes of the interior valleys of the northern and central Rockies (Schmidt, Shearer, and Roe, 1976). The seed source needs to be downslope of the area to be regenerated, so that seasonal dry winds that come from the valleys are effective. The width of the clearcut areas is often restricted by distances of effective seed dispersal. Various research has shown how the control over the width of openings can determine whether

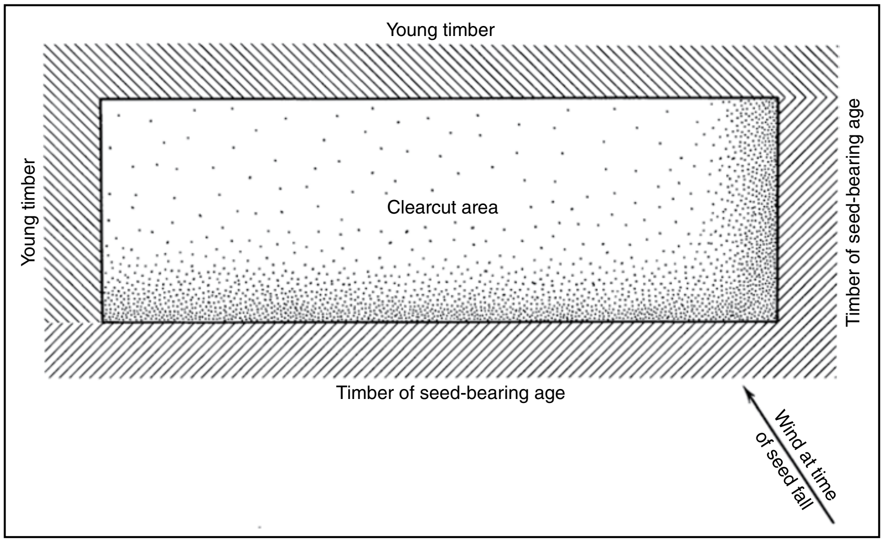


Figure 8.1 Seed dispersal patterns within a clearcut opening. *Source:* Mark S. Ashton.

yellow, paper, or gray birch dominates regeneration in some northern hardwood forests (Marquis, 1966; Smith and Ashton, 1993; Liptzin and Ashton, 1999).

As will be described in Chapter 9, the difficulties of producing seed dispersal over long distances can be mitigated by reserving individual trees, uncut strips, or groups of trees as sources of seed within the clearcut area.

Landscape Scale Patterns of Operation

Substantial research has demonstrated that true clearcutting as a silvicultural natural regeneration method is a sound method for the right circumstance and species (Isaac, 1943; Wahlenberg, 1965; Marquis, 1966; Schmidt, Shearer, and Roe, 1976; Lotan and Perry, 1983; Safford, 1983; Chrosciewicz, 1990). However, the scale and arrangement of stands at which it is applied is a problem, and there are many examples of inappropriate use. The major issues around clearcutting can be categorized as low aesthetic and amenity values, high fragmentation of the original forest structure and interior forest habitat, and increased proneness to windthrow, fire, and landslides. Such issues can be mitigated by careful planning in time and space.

First, there is growing evidence that any attempt to recreate the scale and intensity of natural disturbances with clearcuts, needs to consider the pattern and amount of variability in edge, opening sizes, and woody debris structures (Niemela, 1999; Cissel, Swanson and Weisberg, 1999; Niklasson and Granstrom, 2000; Bergeron *et al.*, 2002). Much of this work has been done in the Canadian boreal and the US northwest, matching clearcutting arrangement, site treatment, and timing, with known natural patterns of fire size, intensity, and return interval (Cissel, Swanson and Weisberg, 1999; Bergeron *et al.*, 2002).

Second, spatial modeling tools can be used to quantify landscape-scale structures and patterns into indices that can then be used to assess proposed landscape-scale cutting operations (Haines-Young and Chopping, 1996). For example, Li *et al.* (1993) showed from simulations that aggregating and creating larger stands for clearcut applications was preferential in reducing edge and forest fragmentation, and in so doing, created higher wind firmness and more interior forest structure for certain wildlife.

Third, natural disturbances that are large can often have wide ranges of stocking, with some areas failing to regenerate or taking many years to recover. To overcome seed dispersal limitations, when stands are purposely large, adequate seed dispersal can be achieved by sequential or alternate cutting of the stand that is completed over a short period of time (e.g., 2–3 years) (Fig. 8.2). The alternate strips of trees within the stand act as a nearby seed source to regenerate the opening and technically are a temporary source of seed within the stand. Such an operation allows a clearcut to emulate the scale and intensity of a natural disturbance, but more predictably secure an even distribution of regeneration to meet commercial demands of establishing a new crop quickly, mitigating any detrimental erosion effects from unoccupied growing space, and meeting green-up regulations.

Site Treatments Associated with Seeding from Adjacent Stands

As previously stated, treatments associated with true clearcutting that prepare the soil surface for seed that are dispersed from outside the stand, are considered lethal. They are some of the most severe site treatments that accompany a regeneration method. In most cases, particularly where there is no fiber or biomass market, slash residue from the harvest can be broadcast burned to simulate a more controlled condition of a wildfire that prepares the seedbed for regeneration. Such burns can still pose a risk of escape, so pile-and-burning is an even more controlled alternative, particularly when piles are burned during the wet or cold period of the year (see Chapter 7 for details) (Table 8.2). The purpose of both kinds of burning is to expose mineral soil for best

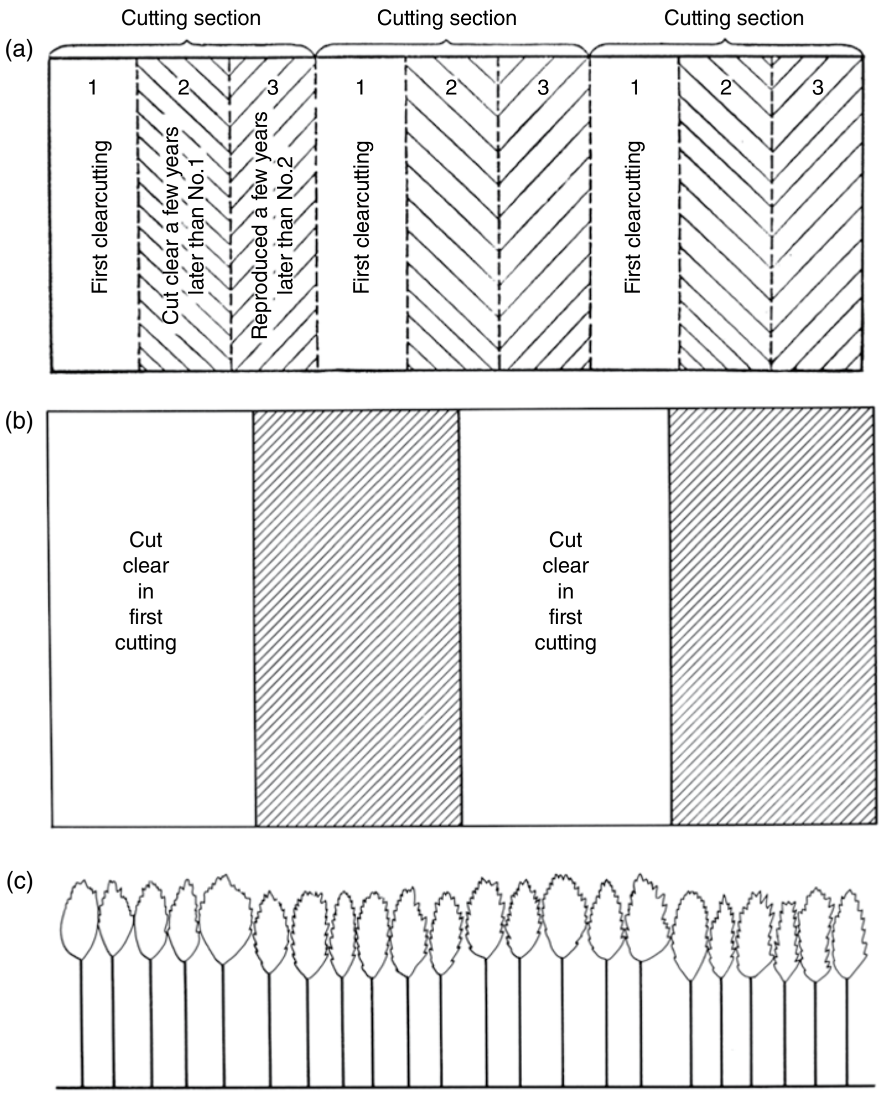


Figure 8.2 The pattern of operation to ensure seed dispersal by: **(a)** sequential strip clearcutting; or **(b)** alternate clearcutting of a stand. **(c)** A profile of stand development post clearcutting, showing the small difference in height due to regeneration lag of the strips that were cut last. *Source:* **(a–c)** Yale School of Forestry and Environmental Studies.

Table 8.2 Site treatments that are often used with true clearcutting.

Treatment	Example
Surface soil preparation	
Usually several treatments are done in combination with each other to be most effective	Pile and burning Chopping and crushing Broadcast burning Root raking and scarification Windrowing Disking and bedding
Reducing competition	
	Broadcast foliar application of herbicide Prescribed groundstory fire

Source: Mark S. Ashton.

germination of light-seed species. After pile-and-burning, some additional scarification or use of herbicide for vegetation control may be needed.

Where fire cannot be used because of air-quality or wildfire-risk concerns, the alternatives are few and often less desirable. Piles can be left unburned, scarification can be done, and/or broadcast application of herbicides can be used to control residual sprouting or seedbank vegetation.

Where natural disturbances are less severe, desired site preparation can be less intensive. The combined use of herbicides and scarification in these cases can be the most effective site treatments. An example is the coastal plains and uplands of the southern US where natural fires are more frequent but less severe as compared to certain interior boreal or intermountain areas.

A concern for many of these kinds of intensive site treatments where there are strong energy and chip markets for woody biomass, is the desire to harvest nearly the entire site such that there is no debris left to burn or to rot in place and return carbon and nutrients back into the soil. Temptation to use everything on marginal sites needs to be avoided at all costs.

Clearcutting with Regeneration from Seed on the Site

The restrictions set on the size of clearcut areas by seed-dispersal distances can clearly be avoided, if a supply of seed is stored on the trees or in the soil. With almost any species, a substantial amount of seed may come from the trees removed in clearcutting, provided that the cutting is made just before or after the release of seed in a good seed year.

With most species, the only seed from the cut trees that is useful for regeneration is that which is produced in the current year. Among the exceptions are certain conifers that have stored seed in serotinous cones that open gradually over a period of years, as is true of black spruce, or that rarely open to any extent except under the influence of high temperatures. The most prominent species in the latter group are the jack and lodgepole pines of the northern US and Canada (Lotan and Perry, 1983; Chrosciewicz, 1990) (Fig. 8.3). Many other localities that are subject to hot fires also have pines that reproduce in nature after crown fires. Seed stored in serotinous cones remains viable for many years, but special measures are often necessary to create the release of this vast quantity of seed after cutting.

Some eucalypts have seeds stored on the trees that are released in abundance after hot fires. This is true of the second tallest tree species on earth, the mountain ash of southeastern Australia (Hillis and Brown, 1984). Investigations in Tasmania have shown that it is necessary to create substantial amounts of dry fuel for prescribed burning to prepare seedbeds after clearcutting. The fuel includes not only the logging debris from the mountain ash, but also that from the deliberate felling of small non-eucalypts of the understory. The resulting hot fires induce mountain ash regeneration without destroying much of the organic matter incorporated in the mineral soil. Alternatively, less severe fires can induce regeneration of less desirable eucalypts.

Adequate amounts of seed of a few species may remain viable in the humus layers beneath uncut stands for periods longer than 1 year. One example is Atlantic white-cedar, the seeds of which are stored in large quantities in the poorly aerated peats on which this species grows (Little, 1950). Another is yellow-poplar (Clark and Boyce, 1964), which requires high temperature or exposure to light in order to germinate. The seeds of the ash remain stored in the forest floor for 1 year because they take that

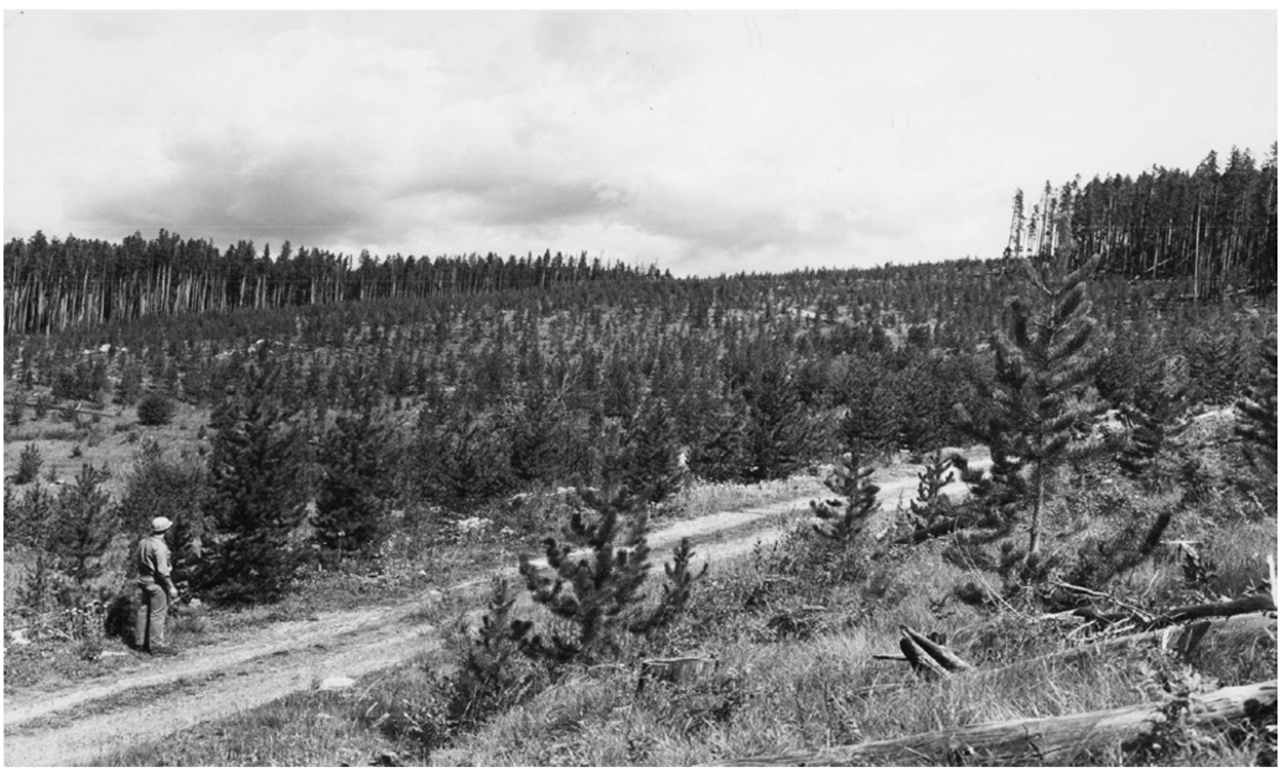


Figure 8.3 A young stand of naturally regenerated lodgepole pine with older stands adjacent to it. *Source:* US Forest Service.

long to mature after they fall from the trees. With such species, it is often possible to expect seemingly miraculous regeneration after removing the entire standing source of seed. However, it would be important to make sure that the seeds are on the site before proceeding.

Long-term storage of seeds in the forest floor is more characteristic of pioneer trees, annuals, and shrubs. Many of these species have seeds with hard, nearly impermeable coats that allow the embryos to survive for the many decades that may elapse between major fires or similar regenerative disturbances. They germinate or flourish long enough to produce seeds and then die or lapse into the understory. Examples of such species are in the genera *Rubus*, *Ribes*, and *Ceanothus*, as well as the short-lived pin cherry.

Site Treatments Associated with Regeneration of Seed on the Site

Site treatments for clearcuts that rely upon a seed bank or seed source within the forest floor or within the remaining slash, can be treated similarly to that for seed that is dispersed from adjacent stands. Seeds that are within serotinous cones should have the branches distributed evenly across the stand, and then the site should be broadcast burned (Chrosciewicz, 1990). If fire cannot be used, a useful alternative is to first pile the branches, scarify the soils, and then evenly redistribute the branches across the site prior to the heat of summer. The cones will open with the high surface temperatures, and this is sufficient to disperse the seed that will then germinate. Seeds that are within the organic horizons of the soil surface need to be exposed to mineral soil and warmth from the sun by scarification (Leck, Parker, and Simpson, 1989; Thompson, 2000) (see Table 8.2).

Applications of True Clearcutting: Case Studies from North America

West Coast Douglas-Fir Region

The most common criterion of adaptability to clearcutting is the capacity of a species to grow faster in height than the undesirable competitors. This is why clearcutting is not well suited to those kinds of shade-tolerant species that grow slowly in the juvenile stages. The pioneer vegetation (which includes the desired trees species) grows so much faster than the shade-tolerant species that it would require a great deal of release work to maintain them in the rapid vegetation growth.

The evolution of silviculture in the west coast Douglas-fir region provides a good illustration of the development of the silviculture of pure even-aged stands. Historically, under entirely natural conditions, coastal Douglas-fir often regenerated after lightning fires. The sources of seeds were scattered seed trees or patches of trees in swales that escaped fires or were not promptly killed by them. Douglas-fir, which is normally the fastest growing conifer of these forests, tended to dominate for the first century of stand development. The Douglas-firs then dwindled from the attrition of various root-rots and insects, and were gradually replaced by western hemlocks, true firs, and western redcedar that became established in the understories at the time of the initiating fires or afterwards.

Early in the 20th century, these forests were being liquidated by railroad logging in combination with cable yarding. As a result, clearcut areas were extended progressively along the logging railroads. Even though only the best trees were harvested, the shifting of the yarding cables usually pulled over the rest of the trees, creating huge volumes of slash. Society at that time had no concern for forest regeneration, but it did have the hope that laws requiring broadcast burning of slash might reduce the dangerous wildfires of the time.

Foresters had little to say about what was going on, and even at that, tended to be complacent about the very large size of the clearcut areas. There was the mistaken view that the seeds of Douglas-fir from the old stands would remain stored and viable in the forest floor for many years, even with clearcutting and slash burning. This view was based on the observation of the fine Douglas-fir regeneration that had appeared after fires in uncut stands. Foresters had discounted the importance of wind dispersal of seeds from adjacent stands or from scattered survivors. They did correctly perceive that a quick repetition of tree-killing fires would eliminate the conifers because the seed supply would be destroyed, whatever its source. Unfortunately, the otherwise good research that had been done about the regeneration process had omitted any good test of the long-term viability of Douglas-fir seeds.

By the 1930s, it was shown (Isaac, 1943) that retention of living seed sources was crucial. Foresters began to have some modest influence on harvesting practices, and interest arose in regeneration provided that it cost little. For the first time there were tractors and trucks powerful enough to move the huge old-growth trees that could previously be logged only with cumbersome steam-driven machines. However, only the biggest and best trees had enough value to be harvested.

These circumstances set the stage for ill-fated efforts to prolong the lives of old-growth stands by light partial cuttings referred to as "selective logging." The cuttings were intended to operate as selection cuttings to create uneven-aged stands (Curtis, 1998). The only trees cut were commonly those roughly 3 ft in diameter (1 m); these were mostly the scattered surviving Douglas-fir, which in spite of their great size and age, were still the most durable trees in the old stands. Unfortunately, most

of the remaining trees were western hemlocks and true firs. The usual result was an acceleration of the process by which wind, fungi, and bark beetles break up ancient stands. By the 1950s, the whole episode was recognized as a fiasco to be quietly forgotten.

During the next phase, clearcutting returned to fashion. By then it had been found, at least on the most common kinds of sites such as those in western Washington, that reasonably good natural regeneration could be obtained from wind-borne seed, if the clearcuttings were less than about 100 acres (40 ha) in size. It was also found that if a few seed trees were left within the cutting areas, the regeneration was better than when reliance was placed on adjacent uncut stands.

By the 1960s, however, attitudes toward forest cutting had changed to the point that state laws required forest regeneration. The large operations with cable-logging in old-growth timber also made it desirable to clearcut areas that were too wide for natural seed dispersal. Thus, there was a period during which aerial direct seeding was a common way of regenerating after clearcutting and broadcast burning of slash.

Planting has subsequently become very common because of the willingness to invest money to ensure the prompt regeneration of properly spaced trees of the best available genetic qualities. Nevertheless, the evolution of silvicultural practice does not stop. It was soon found that the routine of clearcutting, burning, and planting was not a universal solution for the silviculture in the west coast Douglas-fir region. It tended to fail when efforts were made to extend it to sites that were either too wet or too dry.

The most complete failures were at high elevations in the Cascade Range, where there are severe microclimatic extremes, and the true firs were the main species. Plantation failures were also common on certain sites in southwestern Oregon, where the rainless summers are longer than they are farther north (Seidel, 1979). True clearcutting with site preparation often produces eruptions of red alder and undesirable shrubs when it is extended westward into the narrow coastal fringe. The fog-drip precipitation supports luxuriant stands of western hemlock and Sitka spruce, which are advance-growth species.

Another general problem associated with silviculture in the northwest in the recent past, especially on public lands, was the popular displeasure over the ugly appearance of clearcut areas. Although the use of shelterwood methods has increased somewhat, there is a remaining tendency to cling to clearcutting and planting as a standard operating procedure. Popular acceptance of plantation silviculture might be greater if it were simply limited to the numerous cases where it is essential. Currently, natural regeneration in the Douglas-fir type is less common than in any other forest type in the Pacific Northwest. The Forest Practices Act requires planting in northwest Oregon where there must be germinants the year after harvest in order to produce 3-year-old seedlings, 2 years later, something that is virtually impossible to achieve with natural regeneration. The requirements for other areas are less restrictive, but general practice is to routinely plant on all areas that are harvested. Also, the intermittent seed crops, the seed- and seedling-eating animals, and the particular susceptibility of newly germinated seedlings to extremes of heat and drought make reliance on natural regeneration too risky for areas under commercial timber production.

Southern Pines

The same sequence of events has somewhat taken place in the development of the silviculture of southern pines on the southeastern coastal plain (Williston, 1987). Initially, there was widespread devastation from the combination of land clearance and annual burning to improve grazing. Most first attempts at long-term silviculture took the form of selection cutting. These efforts proved to be fairly effective as a means of managing existing growing stocks but were not very compatible with the hardwood-control measures necessary to establish pine regeneration.

The period 1950–1970 witnessed the same quick progression from one method of establishing even-aged stands to another, mainly on industrial forests. Initially, the seed-tree method was the solution, but this method was generally replaced by aerial seeding when it was concluded that each technique required the same amount of site preparation. Then, when industrial owners became willing to spend money for prompt regeneration with well-spaced pines of good genetic qualities, planting became the common technique (Wahlenburg, 1965).

One useful illustration of the way silvicultural prescriptions should be fitted to the circumstances comes from observations in the well-watered loblolly pine stands of coastal South Carolina (Lotti, 1961). Thus it is possible for systematic programs of thinning and prescribed burning to enable natural regeneration by clearcutting throughout more than half of almost any year. The development of good seed bearers by thinning stands provides ample seed for regeneration almost annually. Regeneration is then effective if litter and understory hardwoods are sufficiently reduced by prescribed burning. Harvests between March (the time of germination) and September (when the seedling stems harden) are the exceptions; during these 7 months it is necessary to reserve seed trees to allow recovery from any losses from logging damage to succulent seedlings. During the remainder

of the year, either the newly fallen seeds or the hardened first-year seedlings provide enough regeneration to allow clearcutting.

Actually, almost any method of regeneration can be, and is, used in regenerating southern pines. Other methods are used for meeting various management objectives, best achieved by partial cutting systems. Regeneration of the southern pines can be obtained by almost any method that provides for controlling competition from hardwoods, if there is enough sunlight and pine seeds or seedlings are on the ground (Hu, Lillieholm, and Burns, 1983) (Box 8.1).

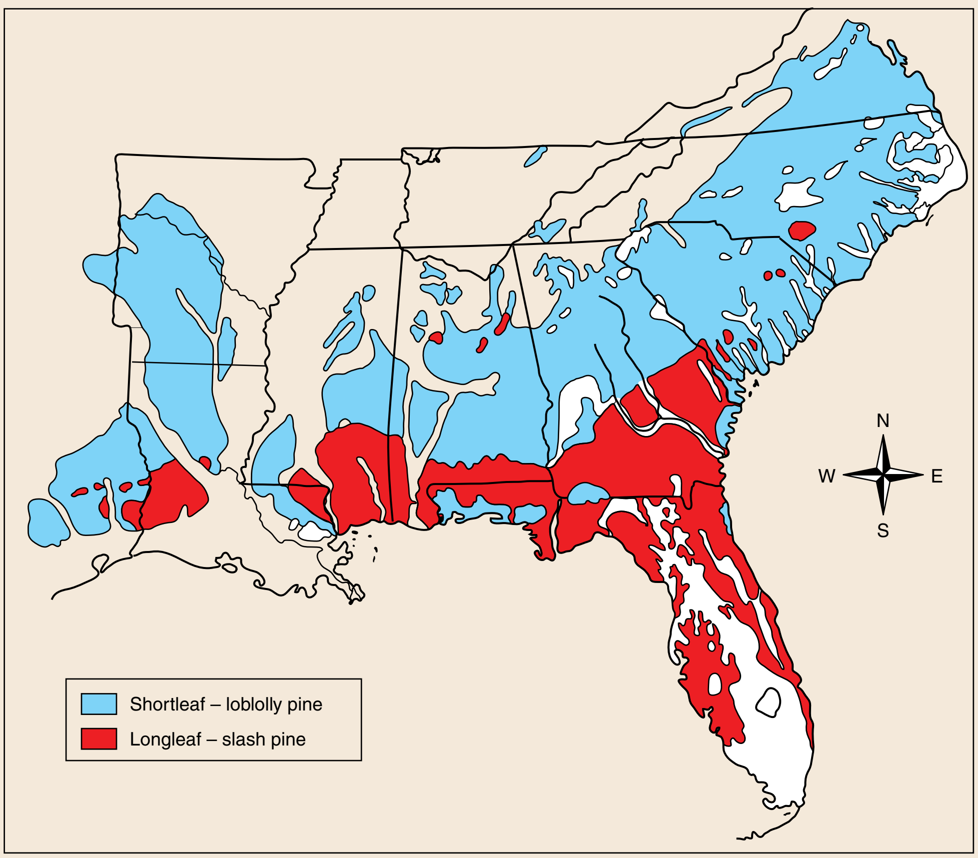
Box 8.1 Regenerating southern hard pines on the Gulf Coasts of Mississippi and Alabama using the strip clearcut regeneration method.

Introduction

In the southeast region, pine plantation forestry is now the dominant mode of regeneration (Fig. 1). Historically, many private landowners worked with natural regeneration and some still do, particularly to improve wildlife habitat (Kushla, 2009). Southern pines are long-lived shade-intolerant pioneers that grow well in open conditions. To varying degrees, most are adapted to fire. The most adapted to surviving fire as a standing tree that provide a seed source are longleaf and slash; Virginia and sand pine are more likely killed standing but the cones on their branches exhibit serotiny. Southern pines can be regenerated in a number of ways through clearcutting, seed-tree, shelterwood, or selection methods.

Regeneration

The clearcut strip method is a technique suitable for pines that have prolific seed production and relatively frequent mast years (e.g., loblolly, shortleaf, and Virginia pines) (Fig. 2). Logging should be done on the leeward side of prevailing winds in approximately 200-foot-wide strips to ensure adequate seed from the adjacent mature stand (Kushla, 2009). After logging, site preparation that includes crushing and chopping the groundstory slash and scarifying the soil surface is important. In certain circumstances, slash may be piled and burned or broadcast burned. Spring burning often helps facilitate seed dispersal of Virginia pine slash because of its cone serotiny.



Box 8.1 Figure 1 Pine forest type distributions for the major southern pine species of the southern states. *Source:* Adapted from USDA Forest Service.

(*Continued*)

Box 8.1 (Continued)

Box 8.1 Figure 2 Fifteen-year-old loblolly pine (*Pinus taeda*) being harvested in a strip clearcut. Slash is being chipped and the soil surface is being scarified for seed dispersal from the adjacent stand. *Source:* US Forest Service.

The silviculture of the southern pines is very similar to the methods used in other parts of the world for many other two- and three-needle pines. Among these are *Pinus radiata*, which is native to an area of only a few thousand acres on the Monterey Peninsula of California, but grown on millions of acres in Mediterranean climates around the world (Lewis and Ferguson, 1993), *Pinus halepensis* of the Mediterranean, and *Pinus sylvestris*, the most important European pine.

Closed-Cone Pines: Jack, Lodgepole, and Pitch Pine

The species of pines that have serotinous cones are the one important group that is generally more satisfactorily regenerated by clearcutting than by any other method. If the cones are truly serotinous, the seed crops can be stored in the crowns of the trees for many years, and there is no necessity of reserving the standing trees. The main problems are to get the cones to open and to expose enough mineral soil. If all of the cones on standing trees remain tightly closed, it may be futile to reserve any trees strictly for a source of seed. It is not possible to duplicate the severe crown fires that originate these stands, so the effects of the fires must be simulated by other means.

Reasonably successful techniques for this purpose have been developed for jack pine in the Great Lakes Region (Smith and Brown, 1984; Benzie, 1977), and sand pine on the old raised beach deposits of coastal Florida. The lodgepole pine of the Rocky Mountains is quite variable in the closed-cone habit over the range of the species, and so it must be handled carefully with full consideration of the degree of serotiny the tree has within the region of focus (Baumgartner *et al*., 1985; Lotan and Perry, 1983; Schoennagel, Turner, and Romme, 2003) (Box 8.2).

The first step is exposure of the mineral soil by mechanical scarification. If most of the cones are tightly closed, then the cones or cone-bearing slash must be scattered over the area in such a manner so that a sufficient number of cones lie exposed to the sun within 5 in (15 cm) of the ground. Within this zone of sluggish air movement, temperatures may increase to about 120 °F (50 °C), which is the melting point of the resin that seals the cone scales. The necessity of such high surface temperatures poses a dilemma because they cause heat injury to the seedlings, so some of the seeds must fall into small spots shaded by forest debris.

It would be ideal if the scarification could be done before clearcutting, but it is usually done afterward or by appropriate modifications of harvesting procedures. The most common technique is to disk the areas after cutting and then lop and scatter the slash. If these steps are reversed, the cones are likely to be buried unopened. Success can also be achieved if the slash is bunched with bulldozer root rakes, provided that enough cones are broken off and deposited on scarified soil. Sometimes the dense little clusters of seedlings that arise from the opening of cones on the ground pose a difficult kind of precommercial thinning problem. If slash burning is necessary, it must be limited to the part of the slash that

has been bunched into concentrated areas; broadcast burning destroys too many seeds.

These species have great variations in the degree to which the closed-cone characteristic occurs. It is most pronounced where forest fires have been common in nature (Schoennagel, Turner, and Romme, 2003). If the cones do not remain closed and store seeds, it is necessary to employ some sort of alternate cutting or to clearcut in narrow strips and thus depend on seeds from current production. The assumption that these species are always serotinous has led to regeneration failures in cases where reliance was placed on stored seeds that did not exist (Wyoming Forest Study Team, 1971). If some cones open and some do not, it is often necessary to compromise between the two approaches. Variations in cutting practice, degree of scarification, and slash treatment can be employed to reduce the risk of getting excessively dense natural regeneration that is likely to stagnate.

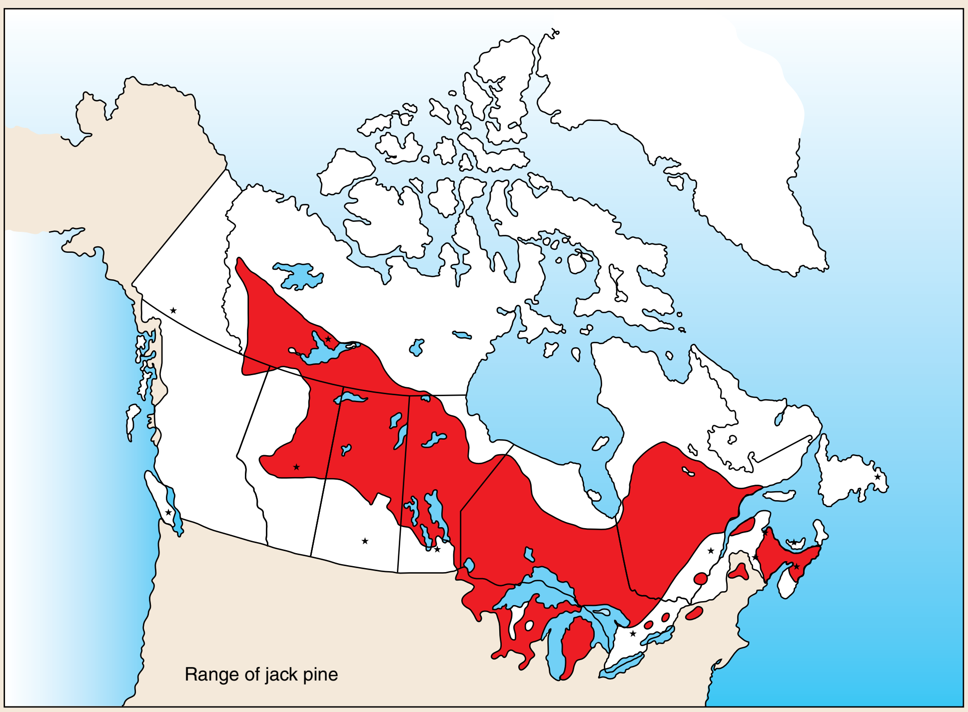
Box 8.2 Regenerating jack pine in the central provinces of Alberta, Saskatchewan, and Manitoba, Canada.

Introduction

Jack pine forests form monodominant stands across a wide range of the interior boreal region of Canada and the US (Fig. 1). Jack pine dominates on poor, sandy soils of glacial loess origin, or granitic soils shallow to bedrock. They predominate on the Canadian Shield, the ancient land mass that is the core of proto-North America. Species associating on the wetter soils include black spruce and, on the more fertile soils, white spruce and aspen. Jack pine is maintained on the poor sites by stand-replacing fires that can occur every 50–60 years and sometimes more frequently.

Regeneration

Jack pine exhibits serotiny whereby the seed is stored in cones that open with heat, either from fire or from the sun. Seeds require open mineral soils for best germination. For this, the true clearcut method is the best method at securing natural regeneration providing the slash with the cones is evenly distributed across the site after harvest (Fig. 2). A broadcast burn can open the cones and distribute the seed or slash exposed to a few hot summer days on top of scarified soils is satisfactory. Summer is therefore the best time for harvesting so soils can be scarified (the snow and frozen ground in winter harvests protects the soil surface from scarification) and seeds germinate with the rains in the next spring. Regeneration is thick and prolific growing fast for the first 20 years or so but very susceptible to fire; by 60 years stands start to show decadence and break apart and the cycle of regeneration needs to be repeated. Jack pines are susceptible to dwarf mistletoe and a number of insects (budworm) and diseases (blights) that fire often controls.



Box 8.2 Figure 1 A range map depicting the distribution of jack pine (*Pinus banksiana*) in North America. *Source:* Adapted from US Forest Service.

(*Continued*)

Box 8.2 (Continued)

(a)

(b)

Box 8.2 Figure 2 **(a)** Two-year-old jack pine established after a clearcut with the slash disked and distributed for seed dispersal and germination. *Source:* C. Merrit, Purdue University, Bugwood.org. Reproduced with permission from D. J. Moorhead. **(b)** Clearcuts and seed tree methods (see Chapter 9) arranged to mimic a natural fire pattern in Manitoba, Canada. *Source:* F. Baker, Utah State University, Bugwood.org. Reproduced with permission from Bugwood.org.

However, if all the cones are truly serotinous, definite efforts must be made to open them; the difficulties are compensated only by the fact that the size, shape, and arrangement of clearcut areas can be governed entirely by considerations other than seed dispersal.

An important incidental advantage of clearcutting in the management of lodgepole pine is that it provides one of the surest means of eradicating infestations of the parasitic seed plant, dwarf mistletoe (Hawksworth and Sharf, 1984). Because the seeds of the pathogen must come from living trees, it is necessary only to prevent slow re-infestation from adjoining stands adjacent to the clearcut areas. With partial cutting, the mistletoe is very likely to spread from the old stand to the new, unless great care is taken to cut all the infected trees of the previous crop (Baumgartner *et al.*, 1985).

The seeds of serotinous conifers rarely exhibit dormancy, so there is little natural control over the season of germination. Therefore, the release of seed should be timed so that the seedlings will germinate at the proper season. With jack and lodgepole pine, the seeds must germinate before summer so that the seedlings will harden before the first frost. With sand pine in Florida, however, it is best to schedule scarification and slash treatment so that seedlings commence development during late fall or early winter, when rainfall is adequate and the risk of heat injury is lowest. It is indeed remarkable how much careful effort is necessary to obtain natural regeneration of these species that are adapted to reproduce themselves so easily and abundantly after catastrophic fires.

Although most hardwoods naturally grow in mixed stands, some that are pioneers in succession can form pure stands and be regenerated by clearcutting. Among these are the birches (Densmore and Page, 1992; Safford, 1983; Marquis, 1966), red alder (Hibbs, DeBell, and Tarrant, 1994), and most eucalypts (Hillis and Brown, 1984).

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9

Natural Regeneration: The Seed-Tree Method

Introduction

In the **seed-tree method**, a harvest is carried out to remove most of the trees in a mature stand, leaving a small number of residual trees (called **seed trees**) to produce the seed for regenerating a succeeding stand. In general, the seed trees are harvested soon after the new seedlings have been established. The stand will have a two-aged structure for a short period, but it will return to an even-aged structure after the seed trees have been harvested. Variations in the method include the seed tree numbers, timing of cutting, and harvest patterns; these are described in detail in this chapter.

Reserve trees can be incorporated into the seed-tree method in order to maintain a long-term two- to three-aged forest structure. Reserves can include intact forest patches and other structures. This method is called **seed tree with reserves**, and is described in detail in Chapter 11. Systems with reserves are defined as **irregular** because of their multi-age-class distribution and their more heterogeneous canopy structure.

The main goal of the seed-tree method is to regenerate tree species that have fairly large seed, often partially wind- or animal-dispersed seed, and are intolerant or mid-tolerant of full sun. The method usually requires bare mineral soil with little or no vegetative competition. Favorable tree species for the seed-tree method include most pines and spruces, Douglas-fir, tulip-poplar, ash, and mahogany, which all have a wing-like structure attached to the seed. However, tree species that produce nuts and rely upon gravity and rodents for their dispersal (e.g., oaks, chestnuts, hickories) can sometimes be successfully regenerated through seed-tree methods as well. Irrespective of their mode of dispersal, most trees that require the seed-tree method are *masting*, meaning that they fruit prolifically, but at very erratic intervals of time (e.g., once every 10 years). Using the functional guild categorization (see Chapter 5), these species would be considered long-lived pioneers of stem exclusion or late-successional canopy dominants.

Species regenerated with the seed-tree method require the same kind of open conditions and lethal site treatments as those regenerated with a true clearcut method of regeneration. The difference is that the focus species in the seed-tree method have seed that is poorly dispersed, and thus needs a nearby parent tree source within the regenerating stand to secure satisfactory stocking. The method of dispersal itself is inclusive of species that regenerate within clearcuts (i.e., dispersed by wind, water, small bird, bat). Species that regenerate prolifically in clearcuts are not dispersal-limited, and will seed into seed-tree treated stands automatically (see Chapter 8). Examples of species that regenerate prolifically without seed-trees include the very shade-intolerant species such as birches, aspens, willows, sycamore, and red alder, which produce quite small seeds that are dispersed in large numbers over long distances. In addition, there are species that germinate from buried seed banks (pin cherry), and species from serotinous cones (lodgepole pine, jack pine).

Seed-tree regenerated stands usually comprise mixtures: pioneers suited to clearcuts as well as the heavy-seeded species that are the focus of the method itself. The seed-tree method does not favor tree species that require partial shade and moisture for germination or that rely upon vegetative propagation. However, the method is often used in combination with clearcuts for species that are compatible with both regeneration methods, especially for species that have some degree of dispersal limitation and site preference for best germination (e.g., Douglas-fir, southern pines). Regional examples where forest types are preadapted to lethal disturbances are therefore in the same types as where true clearcuts are practiced. However, seed-tree methods emulate sub-lethal disturbances (e.g., where several trees survive the crown fire), rather than a lethal disturbance. Seed-tree methods thus reflect areas of a disturbance such as a wildfire, where individual trees survive because of a sheltered aspect or close distance to water that served to protect individual trees. Similar to clearcuts, the seed-tree method is appropriate for many sites in the Intermountain West, the pinelands of the southern US, and the interior fire-prone boreal of Canada (Table 9.1).

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

Table 9.1 Examples of the natural disturbance regimes of forest types and species that can be regenerated by the seed-tree method in North America.

Region and species/ forest type	Regeneration, disturbance regime, and return interval
Interior boreal	
White spruce/aspen	White spruce has a transcontinental range but its core distribution is across the Canadian interior. In this region, aspen is an early successional associate. The return interval for stand-replacing fires is 60–200 years. Aspen immediately responds by root suckering with other pioneers (willow and birch), but spruce seedlings will develop for a longer period of time from seed-tree sources that survive or escape the fire. Spruce overtops the aspen after 50–80 years
Pacific Northwest	
Douglas-fir	The range of Douglas-fir almost extends across all of western North America from the middle of British Columbia to the border with Mexico. Its range is from sea-level in the North to elevations that increase and become more fragmented progressing south in the Rockies. Seed mast years vary with 1 good year in every 7. Given its shade-intolerant and relatively fire-tolerant tendencies, seed-tree cutting is a more secure way of establishing regeneration than clearcutting on more extreme sites within the coastal mountains
Intermountain	
Western larch	Western larch is a deciduous conifer of the central Rocky Mountains that is the shade-tolerant long-lived pioneer, compared to its associates: Engelmann spruce, subalpine fir, western hemlock, western white pine, and interior Douglas-fir. Good seed crops occur about every alternate year, but don't disperse further from the parent tree more than about 150 ft (50 m). The tree is the most fire resistant and windfirm of its associates making it ideal for the seed-tree method of regeneration
Ponderosa pine	Ponderosa pine is widely distributed across the central region of western North America, but not on the coast. It has many growth forms and many common names. The tree dominates stands and forests at the intermediate-to-lower elevations of the mountains, but can be found as a scattered emergent in the more mesic mixed stratified forests of the Sierra Mountains, and interior cedar–hemlock with Douglas-fir at higher elevations. Surface fires were common and patchy prior to colonization, burning at intervals of 5–20 years. Such fires kept these stands open and park-like, devoid of more mesic-loving species. At higher elevations, fires were more of mixed severity, burning more intensely with patches that were stand replacing
Gulf Coast/southeast coastal plain	
Longleaf pine	The distribution of longleaf pine rings the coastal plain from North Carolina to Louisiana, but mostly occupies former marine sediments that are excessively well drained and coarse to poorly drained clays. Its associated species are scrub oaks, and the slash, sand, and loblolly pines. It dominates stands where frequent groundstory burns reduce the understory oak and hardwood component, and promote an open pineland. Return intervals vary from 3–10 years
Middle west	
Bur oak woodlands	Bur oak occurs and dominates the eastern and central forests of the Midwest bordering the tall-grass prairie. It is associated with calcareous soils of ancient inland seas and fine glacial loess of uplands, but can also be an associate of river-bottom forest. Its resistance to fire and its drought tolerance make this tree a dominant of fire-prone woodlands that were repeatedly burned by Native Americans for game, and homesteaders for clearing land. Bur oak masts every 2–3 years, with seedlings that sprout vigorously after surface fires that can occur every 2–5 years
Northern hardwood	
Black cherry/black birch	The black cherry and black birch species are shade-intolerant long-lived pioneers that require mineral soil and a lethal disturbance to dominate a stand without more the shade-tolerant trees that they are usually associated with (sugar maple, red oak, beech, eastern hemlock). No natural disturbance regimes in northern hardwood forests would promote these species alone, unless there was a severe enough wind disturbance (i.e., tornado, hurricane) to be almost sub-lethal. Both species are thin barked and fire intolerant like most northern hardwood species

Source: Mark S. Ashton.

Additionally, seed-tree methods can emulate localized sub-lethal disturbances in a broad range of forest types, such as flooding along rivers, small landslides, and patchy fires, often associated with people and agricultural clearance in wetter temperate and tropical forest types. In fact, many tree species were purposely left in agricultural clearances within the forest (also called swiddens), with the intention of regenerating the old agricultural patches back to forest, richer in timber, latex, and fruit trees that could be harvested later. As in true clearcuts, creation of the necessary conditions for establishment requires heavy-handed site preparation measures.

The Protocol

The seed-tree regeneration method generally involves only three cuts, in the following order.

1) **Preparatory cut**: preparatory cutting may be needed to improve the strength and vigor of trees destined to be left as seed trees. This is needed only for dense stands that contain tall, thin trees with small crowns and poor seed production, which generally result from a lack of thinning in previous years.
2) **Seeding cut**: this cut removes most of the trees in the stand, and opens up a large portion of vacant growing space in a single harvest operation to allow regeneration to develop. This initial regeneration cut is often called the **seed-tree cut**. Site preparation is often associated with the seeding cut; it creates the appropriate conditions on the forest floor for seed germination and early seedling development.
3) **Removal cut**: this cut removes the seed trees and releases the established regeneration to full sun, or nearly full sun. This cut is usually done soon after seedlings are established, but in some cases, the seed trees are retained for a longer period after the seedlings have been established in order to obtain greater timber value from the growth of these seed trees.

The Preparatory Cut

A seeding cut in dense stand conditions would likely lead to windthrow. To solve this problem, a preparatory cut can be carried out several years before the seeding cut, and would generally take the form of a thinning. It could be a heavy low thinning to release growing space throughout the stand, or it could be equivalent to a crop-tree thinning where the seed trees would be designated to remain, and only the trees competing with the seed trees would be cut. The several additional years of growth after the preparatory cut will increase the wind firmness and the seed production of the remaining trees in the stand, and thus the stand will be ready for the seeding cut.

The Seeding Cut

Selection of Seed Trees

It is crucial that the selected seed trees be able to withstand the greater wind speeds that occur after the seeding cut has opened up the stand (Logan, Edwards, and Shiver, 2002). The best trees for wind firmness are those in the dominant crown class that have wide crowns and large live crown ratios; these trees will also tend to have strong tapering stems (Asselin, Fortin, and Bergeron, 2001). If the stand had been thinned in the past or had been a naturally low-density stand, the dominant trees generally can withstand the sudden change in stand density. There are some situations, though, where soils are very shallow and it would probably not be possible to use the seed-tree method at all (Emmingham *et al.*, 2005).

It is also necessary to select trees that can produce abundant fertile seed. Only trees in the upper canopy have enough vigor to produce large seed crops, but a few good seed trees sometimes produce as much seed per acre as the full stand did before the seeding cut. The choice of potential seed trees can sometimes be made by observing numbers of cones or seed fall from trees in previous years. These trees could be marked to be retained as seed trees. It would be ideal if foresters could also choose trees with genetic traits for good stem form, rapid growth rate, and defenses against insect and disease damage. However, because the genotypes of each tree are not known, the selection depends on the observation of phenotypes of the trees in the stand. This amounts to selecting some of the most valuable trees in the stand to serve as seed trees. This is called positive genetic selection, although there is no quantitative measure of potential genetic improvement that can be made just from observation. The very best seed trees are those that have the desired phenotypic traits of tree growth and form, biological defenses, and good seed production.

Number and Distribution of Seed Trees

The number of seed trees to be retained depends on several factors: the size of the trees, the amount of seed produced per tree, the percentage of seeds that are sound (viable), and the number of seeds needed to produce an established seedling, given the particular seedbed conditions. The balance of these factors generally leads to seed tree numbers of about 3–20 trees/acre (7–50 trees/ha) depending upon tree species. A standard pattern for locating seed trees is to have them uniformly spaced as single individuals throughout the stand in order to produce a roughly even amount of seed fall throughout the stand.

Tree seeds can be blown a great distance by the wind, often for many hundreds of feet. The greatest distance

occurs on dry days with strong winds, but most seed disperse from moderate winds and local turbulence. The goal in seed-tree management is to have a seed density that is great enough to meet the need for adequate regeneration. Much of the seed from a tree falls under the tree crown or nearby, which then follows an exponential decline in seed density over greater distance from the tree. For example, about 10% of Engelmann spruce seeds can disperse up to 600 ft (180 m), while 50% of the seed fall was within 100 ft (30 m) of the parent trees (Alexander, 1987). Loblolly pine has a dispersal measure of 73% of the seeds within 100 ft (30 m) of parent trees. Longleaf pine has a heavier seed, and 88% of the seeds fall within 100 ft (30 m) of the parent stem (Boyer 1958). Similarly, trees that produce nuts that are partially dispersed by gravity and by caching territorial rodents or birds, need to be spaced to accommodate dispersal limitations (Gómez, Garcıa, and Zamora, 2003; Forget *et al.*, 2005; Gómez, Puerta-Piñero, and Schupp, 2008). Thus, the importance of high seed density often leads to limiting the distance between seed trees to about 100 ft (30 m).

The number and distribution of seed trees will first influence the pollination of female flowers (angiosperms have flowers and gymnosperms have strobili, but the term “flower” will be used here for simplicity). A few species, such as white ash, cottonwood, and some maples are dioecious; both female trees and male trees of these species must be retained in the stand in order for seeds to be produced. Most tree species are monoecious, having both female flowers and male flowers on each tree. If self-fertilization occurs, it usually results in aborted seed ovules or seeds with poor vigor. However, the male and female flowers of the same tree rarely mature at the same time. In addition, female flowers tend to develop in the upper part of the tree crown, above the male flowers in the lower crown, and the wind is generally not turbulent enough to cause much pollen to rise straight upward. These evolutionary adaptations reduce the amount of self-fertilization. However, if there are only a very small number of trees left in a stand, self-pollination will be more likely to occur (Greene *et al.*, 1999). Thus, a greater number of seed trees spaced more closely together will give an increased chance of cross-pollination, so larger numbers of seed trees will result in both larger numbers of seeds and higher percentages of sound seed in the crop (Box 9.1). To promote regeneration of dioecious tree species (e.g., ash, cottonwood, ebony tree) it is important to ensure that both sexes are represented in the stand, and if there is a desire to increase stocking of the species, then a disproportionate number of female trees need to be left strategically spaced across the stand (Guariguata and Pinard, 1998).

Annual Variation in Seed Crops

Some tree species with small seeds produce large numbers of seed regularly every year. However, many other species with larger seeds have irregular cycles with dramatically different amounts of seed crops each year. These cycles range from 2 years to 10 or more years. Species with these distinct cycles are called **mast species** and the years with the large crops are called **mast crops** (or **bumper crops**). In years without mast crops, most of the tree seeds are consumed by rodents, birds, insects, and other organisms. During a mast year, the high production of tree seeds overwhelms the ability of the seed predators to consume all the seeds. It is during these years that seeds can survive and germinate in large numbers.

Many tree species have variable seed crops, especially the pines, Douglas-fir, and spruce (Cain and Shelton, 2001; Lamontagne and Boutin, 2007), the nut-producing flowering trees like dipterocarps of southeast Asia (Curran and Leighton, 2000), and the oak and chestnut of North America and Eurasia (Ostfield and

Box 9.1 Seed-tree regeneration for shortleaf and loblolly pine on the Piedmont.

Introduction

Shortleaf and loblolly pines grow naturally on the poorer soils of the Piedmont of North Carolina and Virginia with hardwoods such as red maple, sweetgum, and a variety of oaks. It was originally a minor component of the forest prior to land colonization and clearance for agriculture. However, with the abandonment of cotton cultivation (primarily to its decimation by the boll weevil), much of the land came back as pure stands of shortleaf and loblolly pine at the last century and was cutover in the 1940s. Most of the land is now third- or fourth-growth, having been harvested for timber several times over. Most is owned by private landowners interested in a variety of values, particularly outdoor recreation, wildlife habitat, and income from timber, making the seed-tree system very compatible with their interests. Industrial land owners usually rely on more intensive site preparations and plant pure loblolly.

Regeneration

The seed-tree method for shortleaf and loblolly pine in the Piedmont of North and South Carolina relies upon a dependable but periodic seed mast and soil seedbed conditions that expose mineral soil that is moist for germination with high sunlight for seedling establishment (see Fig. 1 and 2). Site preparation requires surface mineral soil

Box 9.1 (Continued)

Box 9.1 Figure 1 Seed-tree cut for loblolly pine (*Pinus taeda*) with broadcast herbicide application prior to scarification. *Source:* B. Lockhart, US Forest Service, Bugwood.org. Reproduced with permission from B. Lockhart.

Box 9.1 Figure 2 Seed-tree cut for shortleaf pine (*Pinus echinata*) with slash that has been chopped and crushed, prior to prescribed burning. *Source:* R. Wittwer, Oklahoma State University, Bugwood.org. Reproduced with permission from Bugwood. Org.

by prescribed burning or mechanical scarification. This process increases contact between the seed and the mineral soil for best germination. Burning and scarification can be done pre- or post-harvest but need to be tied to masting events, as favorable seedbeds quickly become occupied by herbaceous vegetation. Also, seed trees need to be protected from either mechanical or fire damage. The seeding cut needs to be timed to a good seed year (about every 3 years) and should leave 6–12 evenly distributed, well-formed trees per acre (10–30 trees/ha). The number of seed trees left depends on tree size and site conditions. The seed trees should be at least 10 in (25.4 cm) DBH, but preferably seed trees to be left when it comes time to regenerate, can increase the crown vigor and seed production within stands that are closed canopied and that exhibit strong crown competition. If hardwoods are present in the understory, additional site preparation treatments may be necessary using a foliar herbicide to forbs and grasses, a spray application to the basal stems for shrubs, and stem injection to the bole for larger hardwood trees. A delay in seedfall means that the seedbed will likely have to be re-scarified or re-burned (if sufficient fuels exist). A fully stocked stand results in about 1000 well-distributed seedlings per acre (2500 seedlings/ha).

Keesing, 2000; Frey *et al.*, 2007). For example, the seed crop sizes for loblolly pine and shortleaf pine in Arkansas have been studied for 20 years (Cain and Shelton 2001). In that period, there were mast crops of more than 800,000 seeds/acre (2,000,000 seeds/ha) for 6 of the years; good crops of 40,000–800,000 seeds/acre (100,000–1,680,000 seeds/ha) for 9 of the years, and poor crops of less than 40,000 seeds/acre (100,000 seeds/ha) for 5 of the years. In this case, there were never two poor crops in a row, so there would not be a problem to conduct a seed-tree cut with a good crop or better in the 2-year period of seedling establishment. However, other species have longer periods without good seed crops, such as longleaf pine which often have five or more poor seed-crop years in a row.

Site Preparation

Many forest types develop thick forest-floor material and well-established understory vegetation as the stand ages. Most tree species with wind-dispersed seeds need a mineral-soil seedbed for germination, and moderate to full sun for seedling height growth. Similarly, masting species need nuts to be effectively buried, and germinants of masting species do not compete well with rival vegetation. Site preparation may be necessary to create the appropriate forest floor and understory conditions. Prescribed fire, herbicides, and mechanical treatments to scarify or uproot the forest floor can be used to promote the establishment and growth of seedlings. The most efficient approach is to have the site preparation treatments carried out as part of the initial seed-tree harvest. However, if there is a poor seed crop in the year of the seeding cut, then it is possible to delay the site preparation until a good seed year occurs. Site preparation methods are similar to those described for clearcuts in Chapter 8 or in more detail in Chapter 7.

The Removal Cut

The standard practice regarding removal cutting is to have all seed trees cut soon after the regeneration has been safely established. The timing depends on the species growth rates, sites, and climate (Bragg, 2010). The height growth of the regeneration is an indication of how well the seedlings have become established. Foresters will often wait until the seedlings reach 1–2 ft (30–60 cm) in height before making the removal cut. For fast-growing species, such as loblolly and shortleaf pines, that means that the seed trees generally can be cut 3–5 years after the seeding cut. However, with other species it could be more than 5 years, especially in more northern climates with the slower establishment of red pine or spruce. Another aspect of timing with the removal cut is the need to limit damage to the new regeneration. The stems of the young seedlings are flexible enough that they can recover after moderate damage from harvest equipment; however, if regeneration reaches larger sapling sizes, damage from equipment will likely break the rigid stems rather than just bending them, resulting in failure to fully recover.

Dealing with finances, a very different problem, often arises with removal cutting. In some cases, the harvesting costs of cutting the seed trees can often be greater than the value of the timber in the seed trees. Although when the best and largest trees are left, they are usually the most valuable. However, in a situation where the standing seed trees are a financial loss and are not removed, the seedlings will be gradually shaded by expansion of the seed-tree crowns. There are several general options to deal with this problem. One is to plan at the outset to keep a greater number of seed trees than is needed for seed dispersal, so that there are enough trees to have a merchantable operation in the removal cut. This will likely cause some reduction in growth of the regeneration. Another option is to retain the standard number of seed trees, but keep them as reserves for a longer period than is needed for ensuring that the regeneration is well established. These seed trees have no crown competition so they will be growing rapidly; a diameter goal for the seed trees can be set to determine the time of the removal cutting. Again, there will be some reduction in growth of the regeneration. A third option might be to girdle the trees and turn them into snags once their function of providing seed is accomplished. This has the added value of creating old growth and interior forest structures valuable for certain species of wildlife that would not frequent early-successional stands. See Box 9.2.

Box 9.2 Seed-tree/shelterwood regeneration for longleaf pine.

Longleaf pine can be regarded as a shade-intolerant pine, very drought tolerant, and tolerant of groundstory fires. Compared to loblolly and slash pine, seed dispersal is more limited and considerably more sporadic. Longleaf can be very long lived, and prior to colonization it formed extensive stands of old growth across the lower gulf, comprising very open stands on sites that were droughty and relatively nutrient poor. Fire was the natural disturbance regime that prevented the other more fire-sensitive loblolly and slash pines from establishing, and prevented the colonization of hardwoods. The woody understory hardwoods needed to be controlled. Without natural fires the alternative is prescribed burning which needs to be conducted at fairly frequent intervals to maintain the openness for the herbs and grasses with enough space for establishment of the fire-tolerant longleaf pine (Fig. 1).

Box 9.2 (Continued)

Longleaf pine is fire tolerant because of its "grass stage", in which the young seedling takes a period of time to sequester and develop a large tap root and the needles serve to insulate the stem. The even-aged natural regeneration method that is most suited for longleaf can be considered a hybrid seed-tree/shelterwood method, given its autecology. Site preparation involves controlling understory vegetation but not eliminating it, and longleaf itself was relatively more shade tolerant than its close relatives. However, its shade intolerance and its tolerance of drought and fire, and its inability to compete with most other woody vegetation, makes it suited to a seed-tree method (see Chapter 10 for a description of the shelterwood method of regeneration).

Box 9.2 Figure 1 Longleaf pine–wiregrass ecosystems. **(a)** A prescribed fire completed in the fall, prior to seed fall beneath a seed tree cut. The burn was designed to kill hardwood competition back to the ground and to provide growing space for longleaf pine regeneration. *Source:* D. J. Moorhead, University of Georgia, Bugwood.org. Reproduced with permission from D. J. Moorhead. **(b)** The grass stage of longleaf pine depicted with the foliage of three understory oak hardwood competitors (left to right: turkey oak, willow oak and blackjack oak). *Source:* Mark S. Ashton. **(c)** The removal of the seed trees and the release from grass stage of a young stand of longleaf pine. *Source:* US Forest Service.

Variations in Spatial Patterns of Stand Structure

In most seed-tree cutting, the seed trees are isolated from one another and are rather uniformly distributed in the stand. However, other patterns consist of retaining the seed trees in groups, strips, or rows. These alternative arrangements may serve to accommodate other considerations. Concentrating the seed trees in restricted areas (such as linear rows) makes them easier to protect during the initial cutting and also easier to harvest after they have served their purpose. In these strip methods, after the seed trees are cut, site preparation and direct seeding or planting can be used to fill in the open strip areas, if necessary. Arrangement in rows could be appropriate if the method is applied across slopes. The lines of trees could serve both to disseminate seed and protect against surface erosion (Figs. 9.1 and 9.2).

Sometimes seed trees are arranged in small groups instead of isolated individual trees. Using a few carefully selected groups of trees can reduce the edge effect of crown shade on the ground where maximum sunlight is desired and provides greater stability to wind and other elements (Lieffers *et al.*, 1996). These groups are also likely to produce less seed. A preparatory cut several years before the seed-tree cutting would generally be a better alternative unless there are other considerations such as maintaining larger groups of structures for wildlife habitat.

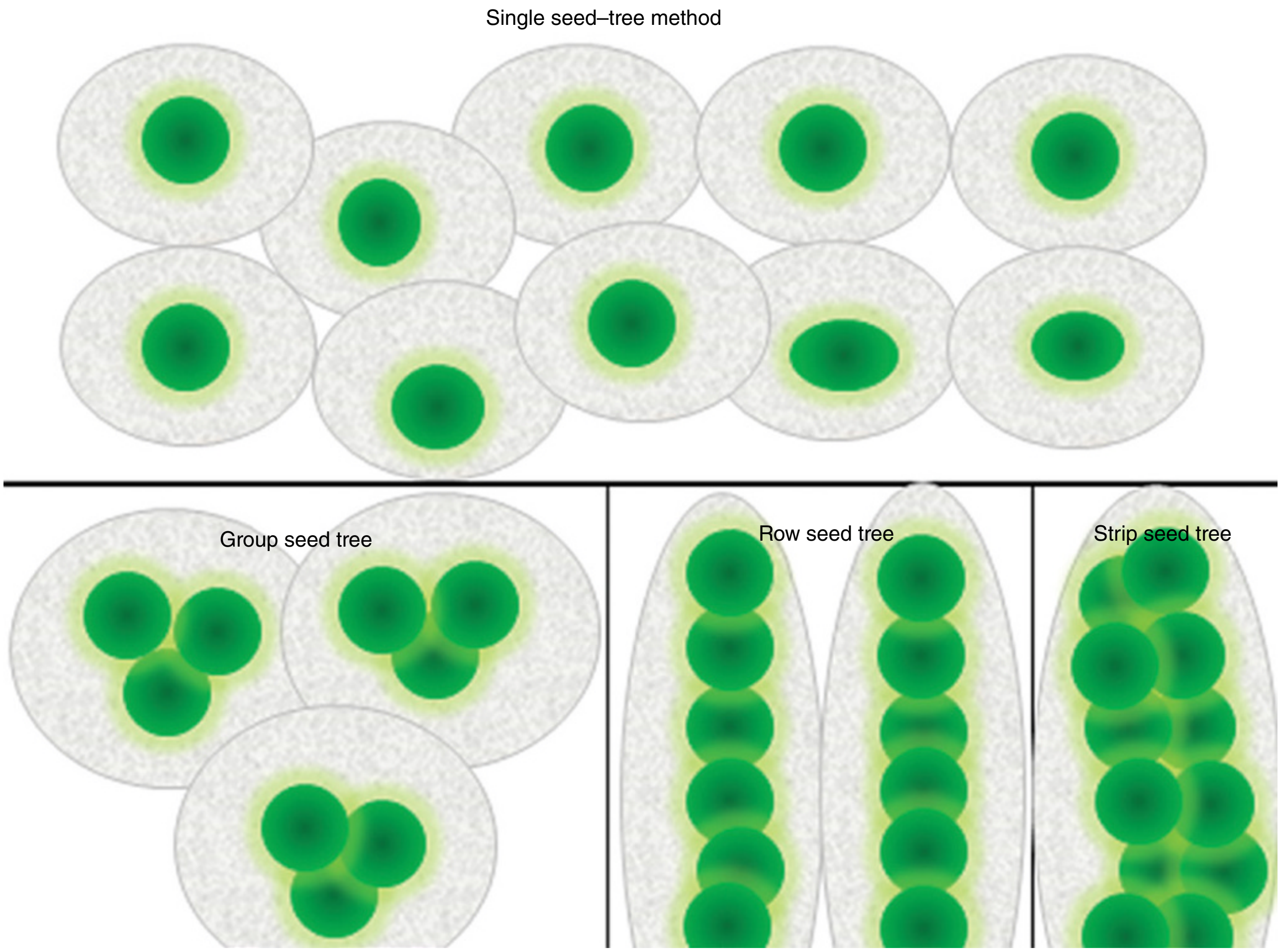


Figure 9.1 A birds-eye view of seed-tree arrangements using single trees, groups, and rows and strips. The usual method is to select trees singly and uniformly across the stand to maximize seed rain and dispersal as depicted in the single seed-tree method, whereby the crowns of the trees are shown in green and their seed-shadows are shown in grey. Trees need to be wind-firm and to be prolific seed producers. Groups are used to reduce the edge effect and maximize solar radiation on the ground surface per unit area of crown or basal area. Groups provide structural support for unstable trees and shelter and habitat for wildlife. Strips and rows aligned along with the contours can be used on steep slopes to mitigate any potential for erosion and to facilitate logistics of harvesting. *Source:* Mark S. Ashton.

(a)

(b)

Figure 9.2 (a, b) The before and after seed-tree treatment for a 95-year-old stand of loblolly pine in the Piedmont, North Carolina. The single-tree method left about 10 trees/acre (25 trees/ha). The larger hardwoods were killed with herbicides and a prescribed burn killed the smaller hardwoods, disposed of the slash, and prepared the seedbed. *Source:* Yale School of Forestry and Environmental Studies.

Application of Seed-Tree Methods

The seed-tree method was used as early as 1450 for regenerating conifer stands in Germany, using single trees and groups of trees for seed sources (Heske, 1938). This method has continued on for centuries in many countries as a low-cost means for establishing new stands, mostly of conifer species (Fig. 9.3a). In the

(a)

(b)

Figure 9.3 **(a)** Scots pine (*Pinus sylvestris*) seed-tree cut in Finland with 25–30 trees/acre (60–75 trees/ha); mean DBH 14 in (35 cm) with slash that has been chipped and taken off site and the soil surface has been scarified. *Source:* D. B. Kittredge. Reproduced with permission from D. B. Kittredge. **(b)** Ponderosa pine (*Pinus ponderosa*) seed-tree cut with 8–10 trees/acre (20–25 trees/ha) in western Montana. *Source:* D. Maguire, Bugwood.org. Reproduced with permission from D. Maguire.

past, the seed-tree method was often used as the initial silvicultural step in regenerating cutover and exploited forests that had not yet been managed. However, about 50 years ago, in order to obtain better control of species and stocking, forest industry began investing greater amounts of money into clearcutting with planting or direct seeding on their timberlands, and placed less reliance on natural regeneration methods such as seed-tree methods. Part of this was the desire to take advantage of the genetically improved plant or seed stock that had become available. Conversely, many private non-industrial landowners have not been willing to invest substantial money at the outset for the costs of seedlings, planting, and site preparation, with the risk that is always present, so seed-tree systems are still very much in operation.

Figure 9.4 Black birch (*Betula lenta*) and black cherry (*Prunus serotina*) seed trees (4–5 per acre) in northern hardwood forest of the Allegheny Plateau, Pennsylvania. *Source:* B. Lockhart, US Forest Service, Bugwood.org. Reproduced with permission from B. Lockhart.

One substantial advantage of the seed-tree method compared to clearcuts is that there is no limit in terms of size and shape of the cutting area. Creating a fully stocked stand from seed dispersal is dependent on adjacent stands to produce the seed fall. Given the locations, sizes, and shapes of clearcuts, there will be many situations where a clearcut might not be successful (Fig. 9.4). The seed-tree method can work regardless of the size or shape of the land because the source of the regeneration is retained on the site. Some examples of seed-tree methods are described here for the southern pine, Intermountain Regions of the US, the oak of the northeast, and the mahoganies of the wet tropics.

Seed-Tree Methods in Southern Pines

Natural pine stands are common across the southeastern US, from Virginia to Florida in the east, to Arkansas and eastern Texas in the west. The most widespread pine species is loblolly pine, which is often mixed with shortleaf pine, especially in the west of the region. These stands usually have a component of hardwood species mixed in, which include red maple, sweetgum, blackgum, and many oak species. There are greater amounts of hardwoods in the eastern range than the west because of the greater precipitation in the east.

Most of the old-growth timber in this region had been cut centuries ago, and the land had been shifted over to agriculture. From 1650–1850, the crops consisted mostly of indigo, tobacco, rice, and cotton. Cotton became the major crop for many decades, but it collapsed in the 1920s because of the invasion of the boll weevil, an insect species that invades and destroys the cotton crop. The abandonment of the agricultural fields provided open land that was a natural seedbed for the pioneer loblolly pine species (Billings, 1938; Bormann, 1953). There was enough natural pine seed in many areas to produce fast-growing loblolly seedlings.

As these old-field stands developed into dense, mostly unmanaged stands, a number of forest researchers began to conduct studies on regeneration of the next forest (Bormann, 1953). The importance of the forest-floor litter soon became clear; pine seeds needed to fall onto the mineral substrate in order to germinate (Grano, 1949, 1954). A standard natural regeneration method for loblolly and short-leaf pine seed-tree methods is to have 4–16 trees/acre (10–40 trees/ha) with trees of about 12–16 in (30–40 cm) diameter at breast height (DBH). The number of trees that are retained varies, depending upon species (generally more for shortleaf), as well as site and seedbed conditions. The goal is to have 1000 trees/acre (2500 trees/ha) of regeneration. Success depends upon proper site treatments in the fall that is timed to masting events at the same time. Seedbed conditions need to be either freshly scarified or burned to expose the mineral soil and to reduce or eradicate any vegetative competition (for more details see Box 9.1 and Box 9.2).

Seed-Tree Methods in the Intermountain Region

Prior to European settlement, the Intermountain Region of the western US had always had strong regional top-down climate drivers such as droughts that influenced the

severity and frequency of insect outbreaks and fires (Heyerdahl, Brubaker, and Agee, 2001). Superimposed on this temporal variation is bottom-up, watershed-scale influences of topography, elevation, aspect, and soil type, that influence the severity and frequency of disturbance. Prior to timber exploitation, land clearance, and grazing, all of these drivers played important roles in shaping the forest composition and structure of the Intermountain forests. Dry forests at lower elevations and hotter southern and eastern aspects were dominated by ponderosa pine to the north (Washington, Oregon, British Columbia, Idaho, Wyoming, Colorado, Montana) or the pinyon–juniper complex to the south (Nevada, Utah, New Mexico, Arizona). Before land colonization and logging, ponderosa pine forests burned twice as frequently and earlier in the growing season in their southern ranges, as compared to their northern range, suggesting longer summers and drier climates in the south. Higher elevation and northern aspects were colder and moister, dominated by subalpine fir and Engelmann spruce, but evidence suggests the same phenomena: more frequent fires in their southern ranges, and less frequent but more

Box 9.3 Using the seed-tree method in western larch.

Introduction

Western larch (*Larix occidentalis*) in the Intermountain Region of western Montana, northern Idaho, southwest Alberta, and southeast British Columbia often grows in mixture with lodgepole pine (*Pinus contorta*) west of the continental divide. Fire chronologies suggest that this forest mixture had fires of mixed severity that ranged from underburns to patches where it was lethal and stand replacing, and which burned at intervals of 25–75 years (Barrett, Arno, and Key, 1991). In addition, there is evidence that in other areas there were much more lethal stand-replacing fires that were infrequent and at intervals of approximately 140–350 years. The mixed-severity fires occurred on lower elevation drier valley areas that are more gently sloping or flat in topography. The latter occurred at higher elevation with more rugged, steeper topographies. In the last 100 years, fire suppression may have changed this to the detriment of the mixture which is fire-dependent, comprising early- to mid-seral species. With no fire, overstocking can lead to greater mortality from insects and disease and to species replacement with the more mesic-loving shade-tolerant subalpine fir, Engelmann spruce, and Douglas-fir.

Regeneration

Regeneration methods for lodgepole pine (true clearcuts) and western larch (seed tree) can be integrated across the landscape to reflect both lethal and sub-lethal stand-replacing fires which would have regenerated these two species on the steeper slopes. Seed-tree cuts for western larch include regeneration of fire-intolerant and well-dispersed seeds of pioneers like lodgepole but focus on larch because of its poor seed dispersal (Fig. 1). Integrated stands across the slope can create a mosaic of true clearcuts and seed-tree methods within which stands along riparian zones and seeps are protected, imitating in a more logistically feasible way a stand-replacing fire across the landscape that varied in severity.

Box 9.3 Figure 1 A seed-tree cut for western larch and lodgepole pine. This example shows a seed tree in the foreground for western larch (8 seed trees/acre, 20/ha) in which the site preparation included chipping the coarser material and distributing the branches but it was not burned. This encouraged some germination of lodgepole and with more larch from the nearby seed trees. In the background is a true clearcut where the same site treatment was applied. Much of the larch seed that germinated came from the adjacent seed trees that were downwind. *Source:* Mark S. Ashton.

severe fires in the north. Abrupt declines in fire frequency in about 1900 from fire suppression and grazing, dramatically influenced patterns in recruitment and regeneration (Belsky and Blumenthal, 1997). Ponderosa pine, in particular, and mixed conifer forests more generally, have undergone large compositional and structural changes that have often led to overstocking. There were subsequent declines in forest health, and changes in fire regimes from ones that were frequent, patchy, and at the groundstory, to ones that are more widespread, with lethal crown fires.

Many of the fire-tolerant conifers, particularly ponderosa pine and western larch, require pre-site treatment fires, masting, and favorable post-seeding rains, all to sequentially coincide (Fig. 9.2b; Box 9.3). The seed-tree method of regeneration is appropriate for such species on the more exposed southern and eastern aspects and higher elevations in the northern regions, and the more sheltered northern and western aspects toward the lower elevations and hotter climates of the south. Regeneration requires site treatments that scarify and expose the mineral soil during the seeding cut. In cases where understory encroachment has occurred with more shade-tolerant, fire-sensitive species, such as Douglas-fir or white fir, preparatory cuts resembling heavy low thinning need be done several years prior to a seeding cut.

Seed-Tree Methods in the Oak–Hickory Forests of the Northeast and Midwest

An extensive literature on the land use of Native Americans suggest that the strong presence of mast-producing trees (e.g., oaks, pines, hickories) is evidence of human fire management and swidden agriculture within forests. Fire is suggested to have been used as a management tool starting around 6000 BCE and swidden farming was at its peak in 1000 BCE (Delcourt and Delcourt, 2004). Oak–hickory and pitch pine–white pine pre-settlement forests of the northeast and central states of the US are suggested to be the signatures of the use of fire and agriculture. These forest types were dominant where pre-European agriculture was intensively practiced in the valleys of the upper Mississippi and its major tributaries, as well as the coastal lowlands and plains of the east coast. The eastern uplands are thought to have been burned to maintain the oaks and hickories for fall nut harvests, for hunting game, and collecting berries.

After colonization and clearance of forests for agriculture, the use of fire was both more extensive and more permanent in nature (Crow, 1988; Orwig and Abrams, 1994; Foster, Motzkin, and Slater, 1998). The current abundance of oak and hickory in the northeastern upland forest is therefore closely tied to this past land-use history of disturbance. Frequent fires and heavy cutting favored oak, chestnut, and hickory because of their ability to sprout; their rootstocks can withstand creeping groundstory fires, which their more shade-tolerant competitors, such as black birch, tulip-poplar, and the maples, could not tolerate (Abrams, 1992; Abrams and Nowacki, 1992). Interestingly, the red oaks predominate on the wetter eastern side of the Appalachians and southern New England while the white oaks predominate in the drier continental regions of the Midwest. Both oak sections (and formerly chestnut) are aggressive colonizers of open habitats as long as there is a nearby seed source, a dispersal agent, and little to no competition from moisture-loving, shade-tolerant tree species. Traditionally, oak and hickory has been regenerated naturally with the use of shelterwoods (see Chapter 10). This makes sense where oak can establish and remain in the understory as advance reproduction, but where it cannot establish because of shade and competition from more mesic-loving species, seed-tree systems are more appropriate. Examples are where second-growth oak forests that have regenerated on mesic sites now face regeneration issues. Many are transitioning to maple, tulip-poplar, and black birch forests because of a lack of sub-lethal disturbance. Site scarification is needed at the time of a seed cutting to promote the oak and hickory. This can be followed after oak and hickory establishment by prescribed fire to kill the thin-barked birch, maple, and poplar. The cutting itself needs to be timed to a satisfactory mast year. Only 10–12 large-crowned dominant oaks of 16 in (40 cm) DBH need to be kept at a uniform spacing of 60–70 ft (18–21 m) (Box 9.4).

Seed-Tree Methods in Tropical Forest Regions

Tropical forests have not been previously thought of as suited to the seed-tree regeneration method until closer examination showed that it has been widely practiced, but under a different name and process. Silvicultural systems of indigenous forest peoples across a wide variety of tropical climates practice swidden agriculture, much like peoples of pre-settlement North America and Europe. Many of these systems reflect the same site treatments and careful planning as a seed-tree regeneration method (Peters, 2000). They can be regarded as managed fallows that start with forest clearance in a large patch with individually spaced trees of economic importance selected to be left standing. Leaving specific trees standing is intended to facilitate their regeneration and enrich the new forest with more desirable species after crop cultivation has ceased. Site treatments are focused toward crop cultivation that is conducted the first few years after

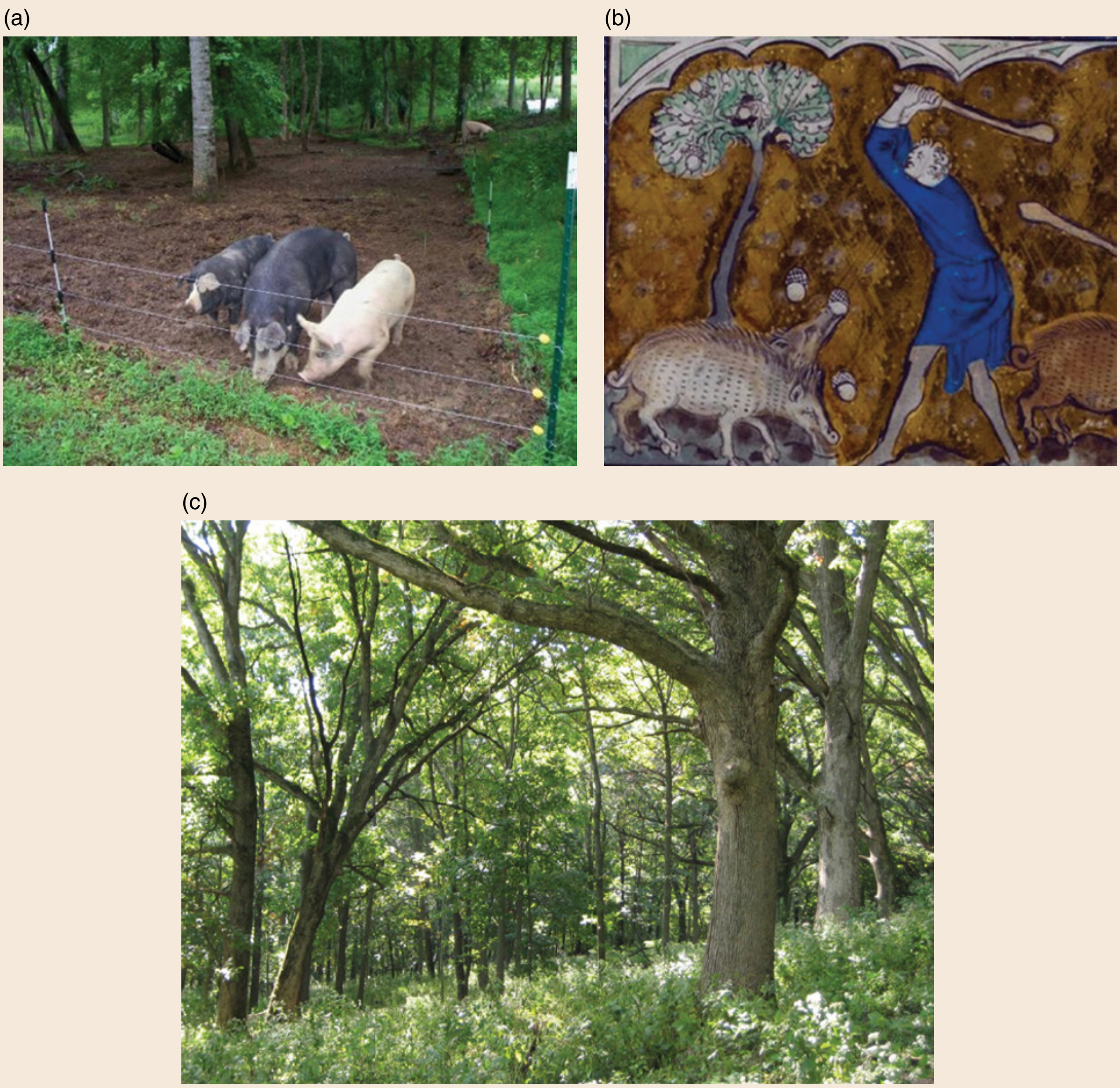
Box 9.4 Ancient oak woodlands and wood pastures.

Introduction

Holm oak (*Quercus ilex*) across the Mediterranean, and sessile (*Q. petraea*) and white oak (*Q. robor*) across central and northwestern Europe were a very important food source for open-range livestock during the medieval period (Pulido and Diaz, 2005). They were cultivated as wood pastures. Open-grown trees provided acorn mast that was beaten down to fatten livestock. In some areas of Spain and Portugal, the "Dehesa" system is still a viable practice. Many small enterprises are starting both in Europe and the US that are emulating this system to produce high-quality pork.

Regeneration

The white oaks as a section are shade intolerant, masting with heavy seeds that are largely dispersed by caching birds and mammals, in most cases near the parent tree (Pulido and Diaz, 2005). Many acorns can be buried by the



Box 9.4 Figure 1 **(a)** An example of what pigs can do to the soil as a site treatment if used carefully and for only a period of time. If left for a long period, serious damage can be done to the tree root systems. *Source:* S. Cox. Reproduced with permission from S. Cox. **(b)** A medieval illustration of beating the tree canopy to drop acorns to the pigs below. *Source:* British Library. **(c)** An example of an old white oak wood pasture that had the understory burned repeatedly. *Source:* Mark S. Ashton.

Box 9.4 (Continued)

Box 9.4 Figure 2 An example of a seed-tree cut for red and white oak in southern New England. The harvest was done in the fall. The slash has been chopped and crushed to the ground and where possible logging machinery has scarified the soil to help bury the acorns. In this photograph there are occasional reserves of small-diameter sugar maple. *Source:* Mark S. Ashton.

over the soil. When acorns germinate, seedlings require high light environments without competition from more shade-tolerant species. The site disturbance by pigs eliminates most competition (Fig. 1a). Fire was another tool used by people to maintain the openness and herbaceous forage beneath the oak. This also eliminates shade-tolerant tree species recruitment but promotes oak old-growth forests originated after wood pastures in Europe, and swidden agricultural fields in eastern North America, were abandoned.

Seed-tree cutting of oak on fertile soils that chops and crushes the slash and scarifies the soil at the time of a mast year is a satisfactory way of securing many species of oak – especially white and chestnut oaks (Fig. 2).

clearance. The first treatment includes prescribed broadcast burning of the residual slash to produce a nutrient flush for crops and to increase mobility for tending and access. This is followed by scarification and weeding to eliminate undesirable vegetation. Young germinants and seedlings from the seed trees are protected during crop cultivation (Box 9.5).

These systems tend to simplify the original forest composition and structure to those species desired for their products, both timber and non-timber (latexes, fruits, medicinals, cordage, etc.). Like seed-tree systems, the species that regenerate well are: (1) the short-lived fast-growing pioneers of the initiation stage that are dispersed by small birds and bats and would come in as seed rain without nearby seed trees, and (2) the focal species of the method itself that would be considered the long-lived pioneers or canopy-dominant/late-successional species that are shade intolerant, masting, and with poor seed dispersal. Many economically important tropical tree species fall into this category (e.g., the mahogany family) and yet western models of tropical silviculture have continued to try to regenerate these trees through modified selection systems (see Chapter 13). There is plenty of documented evidence that selection systems do not work for these kinds of tree species (Fredericksen and Putz, 2003; Ashton and Hall, 2011). However, seed-tree cuts are beginning to be used in Quintana Roo, Mexico (Negreros-Castillo *et al.*, 2014).

Box 9.5 The mahoganies (Meliaceae).

Introduction

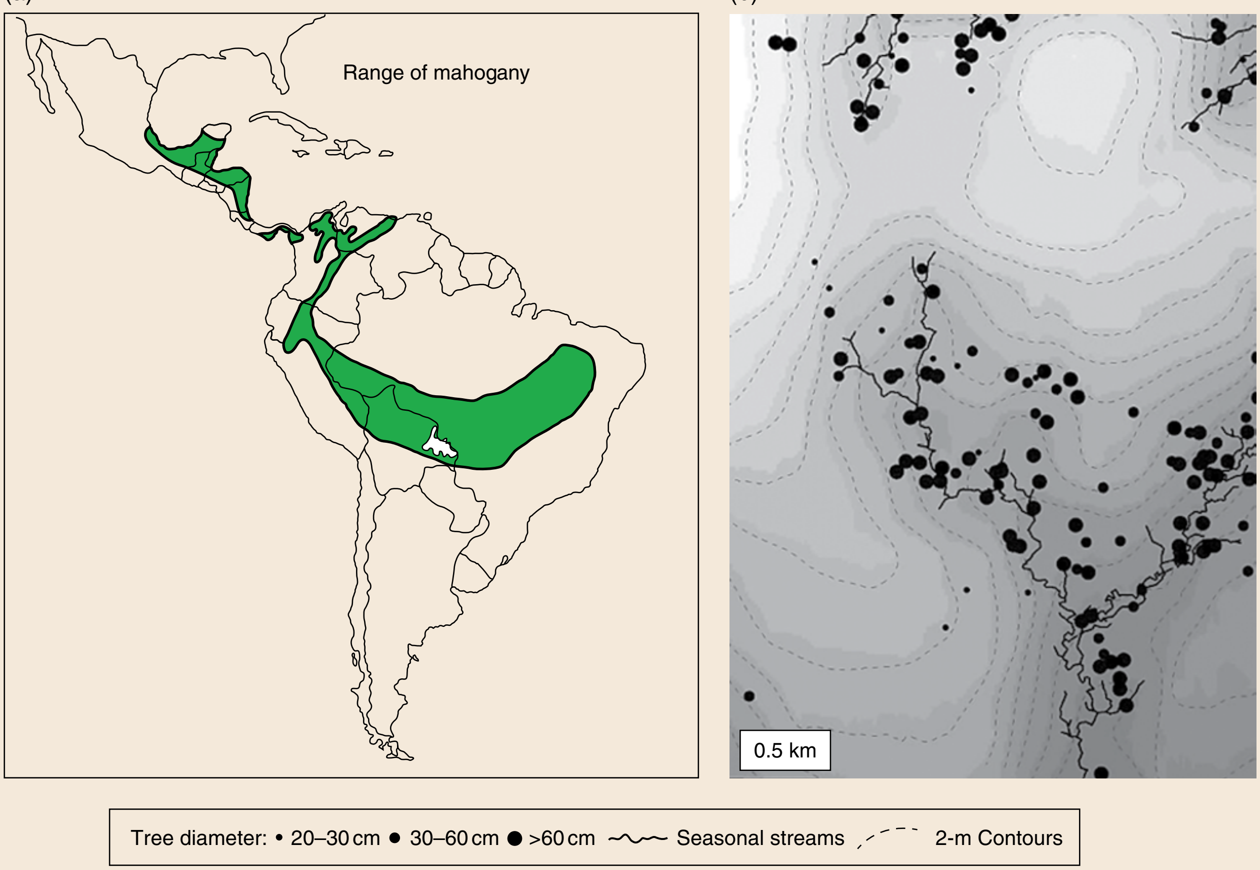
The mahogany family (Meliaceae) comprise many genera across the seasonal evergreen rainforest regions of the tropics. *Swietenia* and *Cedrela* are the two main timber tree genera in Latin America. *Entandrophragma* and *Khaya* are the timber genera of west and central Africa. *Toona* is the genus in Indo-China. All are shade-intolerant long-lived pioneers that get to large sizes within the forest as emergent canopy trees. They require considerable disturbance in order for their germination and growth to compete above their much more shade-tolerant associates. In addition, they are masting species that disperse seeds from capsules that do not travel more than 300 ft (100 m) away from the parent tree. Finally, most of these species are site restricted, often to richer lower-lying soils of topographies that are not noticeably changing. Many studies have examined these genera and wondered how such large trees attain the canopy, but are not easily recruited from beneath.

Strong historical evidence suggests that mahogany does well within swidden cultivation that is associated with fertile soils, and it does well in post-hurricane environments, including fire, and in post-flooding events. All of these disturbances are sub-lethal or lethal for most of the rainforest vegetation except mahogany, which, if the trees survive, can disperse their seed into the openings that are free of competing vegetation. They are strongly episodic at timescales of at least 50 years and in many cases more.

Regeneration

Swietenia macrophylla (big-leaf mahogany) is the most important timber tree in the Meliaceae family within Latin America. Its distribution reflects that of many timber species in the family. It is associated with the more seasonal climates of the Latin American tropics (Fig. 1a) and has a landscape-scale distribution pattern that is restricted to the lower-lying more fertile soils (Fig. 1b). The natural method

(a) (b)



Box 9.5 Figure 1 **(a)** Historical range of big-leaf mahogany in the Americas. *Source:* Adapted from Martinez *et al.*, 2008. **(b)** The distribution of big-leaf mahogany in a 1000 ha (~2500 acre) plot in Para, Eastern Amazonia, Brazil. *Source:* J. Grogan. Reproduced with permission from J. Grogan.

Box 9.5 (Continued)

of regeneration for these trees is by seed-tree cutting. Stands should be delineated by mahogany's restricted landscape distribution patterns and subdivided to accommodate a management regime for a sustained continuous yield. Most of the forest is therefore left untouched, or managed for other products and services. The mahogany stands should be on a sequential rotation. Of course, this never happens. Almost every timber tree in the Meliaceae both in Africa and Latin America is "managed" using diameter-limit logging where all trees greater than 50–60 cm (20–24 in) DBH are cut. There are regulations about reserving some as seed trees but they are not enough, and the environment within which a seed has to germinate and grow, is completely incompatible with its autecology.

Box 9.5 Figure 2 A Milpa swidden, cleared within the rainforest of the Yucatan, Mexico and cultivated with beans, corn, and squash and subsequently abandoned. It is a perfect site for mahogany to regenerate if there is a nearby seed source as seen by the tree in the background. *Source:* J. Grogan. Reproduced with permission from J. Grogan.

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10

Natural Regeneration: The Shelterwood Method

Introduction

The goal of the **shelterwood method** is to establish new even-aged regeneration by gradually opening the canopy of a mature stand, using a series of partial cuttings. These harvests gradually reduce the canopy density of the mature stand. This method is used to promote the establishment of tree species that are mid-tolerant to very tolerant of shade, relative to their competitors in mixed stands, which are shade-intolerant pioneers that often dominate stand initiation and stem exclusion. The method provides only moderate light in the early stages of the regeneration cut. Later cuts will open the overstory to provide greater light for more rapid height growth.

The regeneration guilds of interest for the shelterwood method are the late-successional canopy dominant and the non-dominant tree species that rely upon advance regeneration (Ashton, 1992). Advance regeneration occurs when seedlings germinate and then temporarily grow in the forest understory. They fully grow and establish as a new stand after a canopy disturbance. This means that the kind of disturbance that these trees require to grow into a new stand cannot destroy the groundstory. The disturbance that promotes advance regeneration is categorized as a release type, as compared to a lethal type (see Chapter 5 on regeneration ecology). Shelterwoods emulate release disturbances, as opposed to clearcuts and seed-tree methods that emulate lethal disturbances. Shelterwoods are typically appropriate for the wet and moist forests of temperate and tropical realms (Lowe, 1977; Hannah, 1988). They can also be appropriate for particular fire-sensitive species in drier or more extreme climates, such as the Intermountain west. Species suited to shelterwoods (e.g., white pines, true firs, hemlock) are relatively more moisture loving and shade tolerant than their competitors (Helms and Standiford, 1985; Burton *et al.*, 2000). However, a common exception to this is where mixed stratified forests have long-lived shade-tolerant tree species beneath a canopy of long-lived more shade-intolerant canopy trees species. The most obvious example is the oak and hickory that grows above more shade-tolerant maple where shelterwoods must focus on securing the more shade-intolerant oaks and hickories.

The characteristic species of temperate forests that are appropriate for the shelterwood method include the maples (Godman and Tubbs, 1973; Marquis, 1979), beech (Kelty and Nyland, 1981; Agestam *et al.*, 2003), shade-tolerant birches such as the yellow and black birches (Godman and Tubbs, 1973; Marquis, 1979), red spruce, and balsam fir (Seymour, 1992; Pothier and Prevost, 2008). These species are represented in the northern hardwood (including the Allegheny plateau) and maritime regions of northeast temperate and sub-boreal North America. The mixed oak–pine–hickory forests of the midwest, south, and Atlantic regions do well with shelterwoods on drier soils and in continental temperate climates (Brose, 2010), but do not do well with more shade-tolerant competition (maples, yellow-poplar, sweetgum) on wetter sites (Loftis, 1983, 1990; Schuler and Miller, 1995; Frey *et al.*, 2007). Seed-tree systems can be more appropriate for these species on wetter sites (see Chapter 9), except for the bottomlands where the timing of masting events with more dramatic removals of the canopy are more appropriate as one-cut shelterwoods (see one-cut shelterwoods in this chapter). In the west, shelterwoods are restricted to particular sites and species. Shelterwoods are appropriate for species such as Douglas-fir and ponderosa pine on sites that have more extreme microclimates (southern aspects and droughty) (Benzie, 1977; Youngblood, 1990; Prévosto, *et al.*, 2011). Species on cooler, moister sites and northern aspects would regenerate by seed tree, such as Douglas-fir (Williamsson, 1973). The best-suited species in the west for shelterwoods on the wetter sites include the fire-sensitive and moisture-loving sugar and western white pine, western redcedar, western hemlock, and true firs (Seidel, 1983; Seidel and Cooley, 1974).

Thus, shelterwoods are focused on primarily securing species that rely upon advance regeneration. However, compared to other natural regeneration methods, shelterwoods allow the establishment of other kinds of regeneration such as pioneers and vegetative sprouts. In shelterwoods, the proportions of the different kinds of

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regeneration, besides advance regeneration, are determined by the sprouting ability of species, the degree to which growing space that is not occupied by advance regeneration is available for colonization, and the degree of shade that may limit pioneer establishment. Because of this, shelterwoods tend to promote species compositions and structures that are diverse and complex (Fig. 10.1). It is not by chance that this regeneration method is most

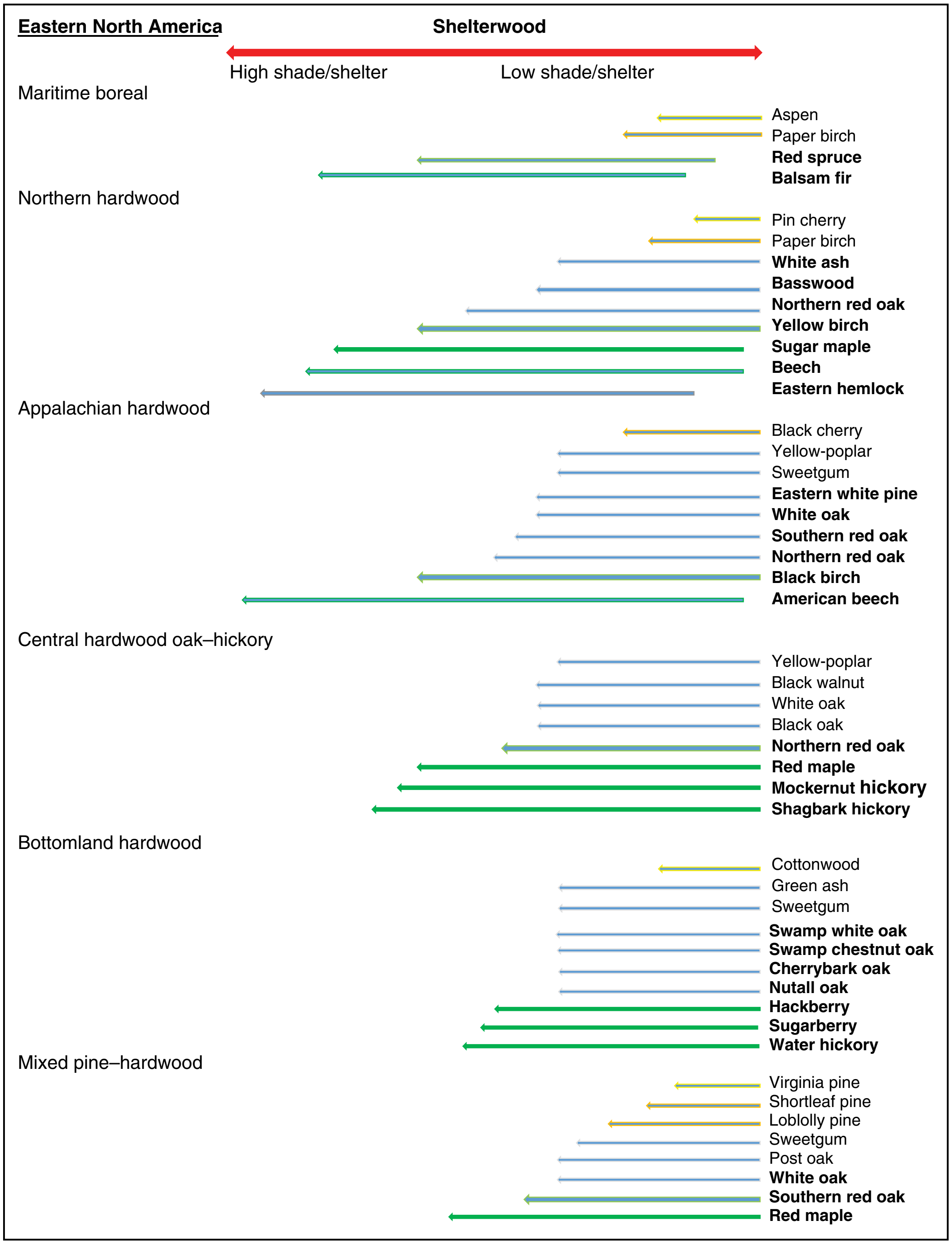


Figure 10.1 Examples of forest types and species that can be regenerated by the shelterwood method. The focus species of shelterwoods for each forest type are in bold. These species predominantly rely on advance regeneration for establishment. The darker the color green or blue, the more shade tolerant the species relative to its associates, and the more amenable to a shelterwood. Other species associates listed are mostly more shade intolerant and will regenerate (indicated by arrows) within a shelterwood, depending upon degree of canopy opening made during the establishment cut, and the nature of site preparation (if any). Shelterwoods with low shade are the most inclusive of all regeneration methods. Those with most shade are exclusive to shade-tolerant advance-regeneration species. *Source:* Mark S. Ashton.

(Continued)

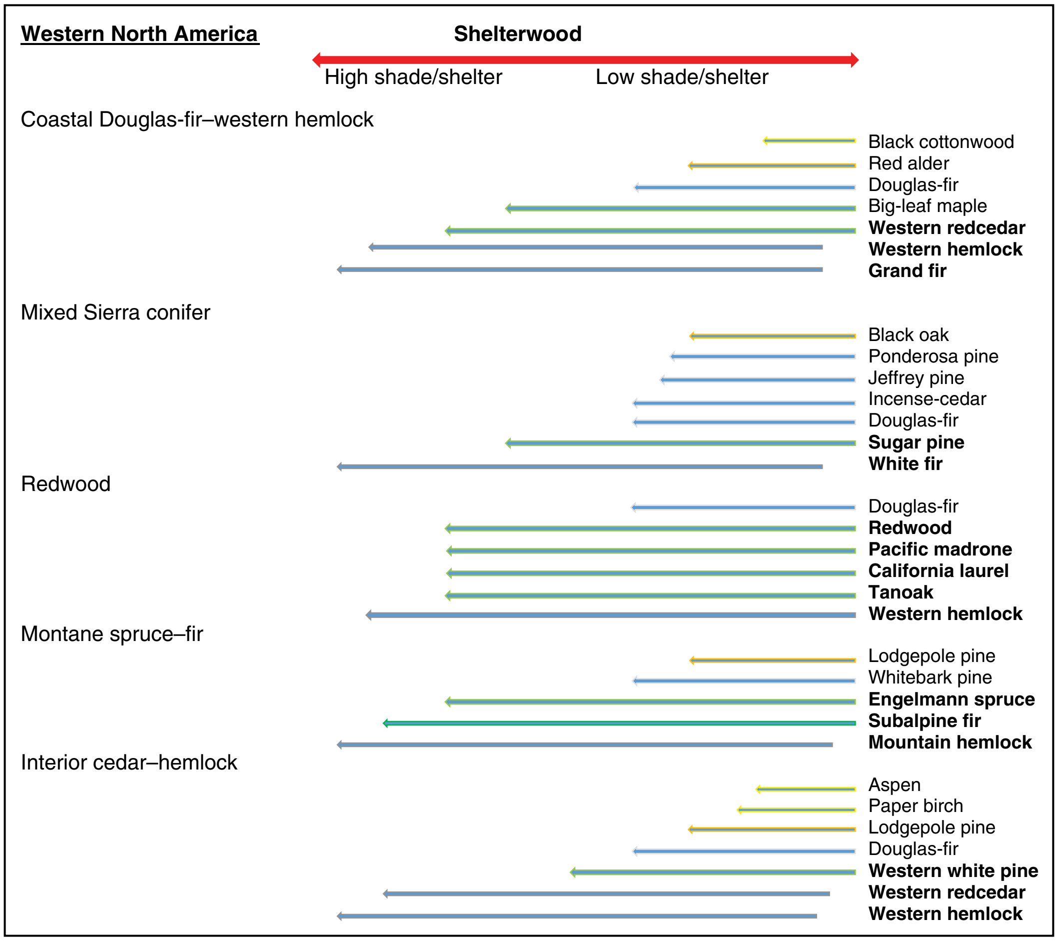


Figure 10.1 (Continued)

appropriate for stratified, mixed, even-aged stands of moist forest regions. As a regeneration method, it is one that can be considered inclusive of a variety of regeneration guilds, where seed-tree, clearcut, and coppice regeneration methods can be considered more exclusive to a particular kind of regeneration.

This method also provides a number of other important benefits. The fact that much of the forest structure of the stand is still intact after the initial establishment cut, means that high-quality timber trees continue to grow, forest habitat structure for wildlife still exists, and the visual aspect becomes a gradual shift from a mature stand to an open sapling stand over a number of years.

The Protocol for the Uniform Shelterwood

The shelterwood regeneration method generally involves two or three stages (Fig. 10.2) to complete the regeneration phase of a new stand, in the following order.

1) **Preparatory cut:** this cut is made to prepare the understory for the germination and establishment of advance regeneration. In many circumstances, if regeneration is already established in the understory, or if there are no impediments to its establishment, then this step can be eliminated.
2) **Establishment cut (or seeding cut):** establishment cuts are designed to emulate a release disturbance where the advance regeneration can establish and grow. This can be a dramatic first cut to open a part of the canopy, or it can be more nuanced, depending upon the shade tolerance of the species being established. Increasing the light opens up the growing space for the release of existing advance regeneration and the establishment of additional regeneration in the vacant areas of the groundstory. Canopy shade made in the establishment cut is the main regulating factor defining shelterwoods. This cut is often simply called the **shelterwood cut**. The term "**uniform**" comes from the fact that this cut is uniformly applied across the stand, such that the spacing between the remaining overstory trees that defines the shelterwood is relatively even. Site preparation is often needed to create forest-floor conditions for seed germination and to reduce understory vegetation.

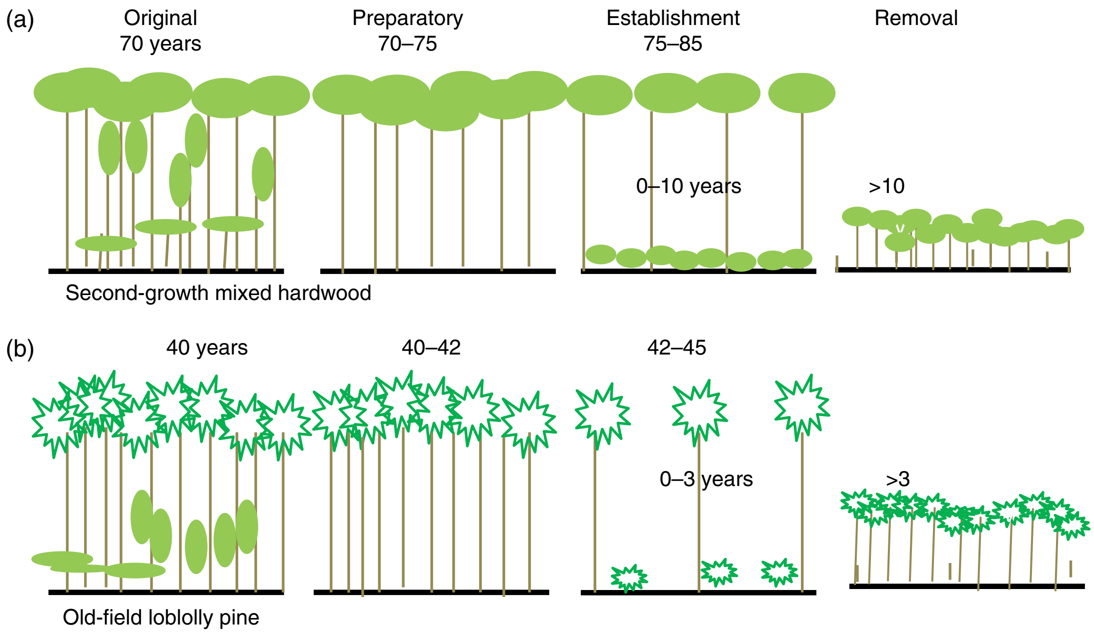


Figure 10.2 Two illustrations of the three stages to a uniform shelterwood for establishing regeneration. **(a)** A 70-year-old even-aged mixed-stratified hardwood stand that had a preparatory cut, taking out the lower canopy strata to increase understory light levels for germination of canopy tree seedlings. At 75 years (5 years after preparatory treatment) an establishment seed cut is performed where the canopy seed trees are spaced for shelter and the seedlings beneath can establish and grow. At 85 years, the overstory trees are removed and the approximately 10-year-old regenerating stand is released. **(b)** A 40-year-old loblolly pine stand that has a preparatory cut removing the smaller and overtopped trees at the same time as a prescribed burn to take out the hardwood understory. This is to increase light and expose mineral soil to secure some initial pine regeneration. At year 42, the canopy is spaced in an establishment cut to provide more light in the understory to establish the pine regeneration. A removal cut is done when the overstory is 45 years old to release the 3-year-old pine stand below. *Source:* (a, b) Mark S. Ashton.

3) **Removal cut (or cuts):** these cuts are made to release the established seedlings from the shade of the overstory canopy. The entire overstory that is left can be taken off with a single removal cut, or a series of partial cuts. There is no limit to the number of removal cuts, but generally one to three removal cuts are used. The **final cut** removes all of the remaining overstory trees.

Foresters often describe a shelterwood by the number of cuttings. For example, a three-cut shelterwood would consist of a preparatory cut, an establishment cut, and a removal cut. If the final removal cut retains a number of reserve trees, the method is called **shelterwood with reserves**, which is described in detail in Chapter 11. As with the seed-tree methods, shelterwoods with reserves are termed **irregular** and can include structures with two to three age classes in a variety of arrangements (e.g., Puettman *et al.*, 2009; Raymond *et al.*, 2009), but there is still one dominant cohort that is established and managed for the regeneration cohort.

Preparatory Cutting

There are many reasons why preparatory cutting may be necessary to ensure successful establishment of advance regeneration.

1) Windfirmness and seed crops: as described for the seed-tree method in Chapter 9, preparatory cutting may be needed for stands that are excessively dense. The trees in these stands have small crowns that cannot provide enough carbohydrates to produce large crops of seeds or to increase the size and taper of trees to make them more windfirm. In this case, a moderate thinning is needed prior to the establishment cut. If a heavy establishment cut was made in a dense stand, there would likely be poor seed crops and many tree falls (Ruel, Raymond, and Pineau, 2003). Instead, conducting a preparatory cut that might resemble uniform crown thinning throughout the stand would reduce the competition just around selected trees (see Chapter 21 for thinning). For the average stand and species, the preparatory cut should be carried out about 3–5 years before the establishment cut, if seed production is the main concern, but it would require 5–10 years prior to the establishment cut for substantial tree growth.
2) Closed-canopy conditions prevent understory development because of shade: in mature forests, where some degree of canopy break-up has occurred, the process of understory initiation (see Chapter 4) has naturally triggered establishment of advance regeneration of the late-successional canopy trees. In

Figure 10.3 Photographs of forest understories that need to be removed in preparatory treatments to secure advance regeneration. **(a)** Hayscented fern in an even-aged, stratified, hemlock–hardwood forest of southern New England. *Source:* Mark S. Ashton. **(b)** *Kalmia* thicket (mountain laurel) in flower in a New England Forest. *Source:* Mark S. Ashton. **(c)** Palm understory in hill dipterocarp rainforest in Malaysia. *Source:* Mark S. Ashton. **(d)** Salal in a second-growth Douglas-fir forest. *Source:* C. Evans, Illinois Wildlife Action Plan. Reproduced with permission from C. Evans.

managed forests, particularly in younger second growth, this process may not have happened. Opening up the lower canopy using a preparatory cut that resembles a low thinning, increases light to the groundstory that can facilitate this process (Loftis, 1990; Man and Lieffers, 1999). In other circumstances where stands have been thinned in prior years, this process may have already happened and no preparatory cut would be needed.

3) Clonal understory plants already occupy the groundstory: many forests can develop clonal understories either naturally or from past land-use histories. In temperate moist hardwood forests, this includes various species of ferns, such as hayscented fern (Horsley and Marquis, 1983; Horsley, 1994), herbs and grasses (Harmer, Boswell, and Robertson, 2005; Donoso and Nyland, 2006), ericaceous shrubs (rhododendrons and laurels) (Clinton, Boring, and Swank, 1994; Moser, Ducey, and Ashton, 1996; Beckage *et al.*, 2000), and small trees such as *Carpinus* spp. and witch-hazel (Schuler and Miller, 1995). Similarly, this can happen in tropical forests with understory palms, bamboos, and gingers (Lowe, 1977; Ashton and Hall, 2011) (Fig. 10.3). To remove the understory and prepare the groundstory to encourage establishment of advance regeneration, preparatory cutting with a site treatment is necessary. The understory can be removed with application of herbicides (Horsley, 1994) or by prescribed burns (Brender and Cooper, 1968; Crow and Schilling, 1980; Moser, Ducey, and

Ashton, 1996). The use of fire (Albrecht and McCarthy, 2006) or cutting plus herbicide application can be useful, but it will generally have to be repeated several times (Loftis, 1990). If site treatments are applied, they generally do not involve disturbance to the soil surface like seed-tree methods, but instead serve to protect it and make it available for re-occupation by desired species that rely upon advance regeneration. The major problem in implementing preparatory cuttings and site treatments of this sort is cost. Often, no merchantable timber is taken out, so the landowner loses money in the short term.

4) Understory plants in dry forests prevent tree germination: dry forests with fully developed root systems can appear to be growing in the open with shrubs and grasses in the understory (e.g., *Ceanothus*, manzanita, salal) (Petersen, Newton, and Zedaker, 1988). However, the belowground growing space is fully occupied with roots. To secure advance regeneration in the understory in the establishment cut, it is necessary to take out some of the understory by preparatory cutting, fire, or use of herbicides (McDonald, 1976).
5) Reducing organic surface horizons: in cold, dry regions or in very wet, cool climates, forest-floor litter does not decompose rapidly, so humus accumulates and seeds cannot become established in the thick humus (e.g., spodosols). Conducting a preparatory cutting to open the canopy will provide sunlight to speed the decomposition of the forest-floor material, and to provide germinating seedlings in the establishment cutting, thus getting better access to the mineral soil nutrients and water beneath (Youngblood, 1990; Burton *et al*., 2000; Nilsson *et al*., 2002; Agestam *et al*., 2003).

However, in many cases, these preparatory cuttings are not necessary because their purpose generally has been accomplished by thinning that was made in prior years, and by the natural development of the stand into understory re-initiation (see Chapter 4).

Establishment Cutting

The next step in the shelterwood method is the establishment cut, which is the true regeneration operation. The main objective is to open up enough vacant growing space to allow seedlings to become established. The ideal plan is to open the canopy enough to favor the seedlings of the desired tree species, but still provide enough overstory shade to reduce or eliminate competition from unwanted shade-intolerant species (Fig. 10.4).

Site-preparation treatments, if not done in the preparatory cutting stage, are often needed to create favorable ground conditions so that seeds can become established. These might consist of the removal of understory plants by cutting, use of fire, or herbicides. These treatments are usually applied just before or during the establishment cut. It would be ideal if the establishment cut would occur just before a good seed crop has fallen. However, the shelterwood method has an inherent safeguard because much of the seed source is still retained in the overstory trees, so it is possible to do the establishment cutting, and then, later, carry out the site preparation during a good seed year. The time period to carry out these operations varies by species and forest type.

The trees removed in the establishment cuttings of the shelterwood method come mainly from the lower crown classes. These overtopped trees and shrubs produce much of the "low shade" that reduces light to very low levels in the understory and mid-story. A low thinning (thinning from below) will remove that lower canopy to allow sunlight to reach the forest floor. The cutting will also include some openings in the upper canopy that produces light flecks and larger light patches that give short periods of direct light. With most shelterwood stands, the establishment cutting will remove trees large enough for commercial sawlogs in a harvest operation. Often, a large amount of smaller woody vegetation needs to be removed, generally with herbicide spray or stem injection, or by cutting with a brushsaw.

The appropriate density of the overstory after the establishment cut differs within wide limits, depending on the tree species, its shade tolerance, its seed-dispersal abilities, and the site conditions. It is useful to review light intensity in regard to forest canopies. To use red oak as an example, a fully mature oak stand would have 1–2% of full light at the forest floor, which would not be sufficient to produce oak seedlings (Fladeland, Ashton, and Lee, 2003). With 5% of full light, small oak seedlings can survive but not grow in height, and with 20% of full light, oak seedlings can survive, grow in height, and produce lateral shoots (Frey *et al*., 2007). Cherrybark oak needs at least 50% full sunlight for satisfactory establishment (Gardiner and Hodges, 1998: Lockhart, Hodges, and Gardiner, 2000).

It would seem that using the percent of basal area or some other stand density measure could directly be used to determine the amount of cutting (for example, if 40% of basal area of a stand is cut, there will be 40% more light within the stand). However, this is not true, because there are multiple layers of foliage in a stand, so an establishment cut removing 40% of the stand density may give only about 10% or 20% increase in light on the forest floor. This means that an establishment cut removing 40–75% of basal area may be needed, in many cases, to produce enough light to accomplish the objective of having seedlings become well established in the

Figure 10.4 Photographs depicting the establishment cutting of a uniform shelterwood for: (a) beech–Scots pine on sandy soils in central Germany that removes about half the basal area; (b) red oak–maple–black birch forest in southern New England that removes about two-thirds of the basal area; and (c) balsam fir and red spruce in Maine that removes about one-third of the basal area.
Source: (a–c) D. B. Kittredge, University of Massachusetts. Reproduced with permission from D. B. Kittredge.

understory, depending upon their shade tolerance (Godman and Tubs, 1973; Hannah, 1988). However, the remaining shade is essential, as it provides protection from harsh environmental conditions such as frost or extreme heat on the succulent young seedlings, and can also increase soil moisture and extend snowmelt for dry sites.

Where moisture deficiencies are likely to limit regeneration, an excessively dense overwood may cause too much root competition and interception of precipitation. If heat injury to succulent young seedlings is the primary difficulty, the establishment cutting should be regulated so as to increase the amount of diffuse light admitted from the sky as much as possible without allowing much direct sunlight to reach the forest floor.

The appropriate density of the overwood differs within wide limits, depending on the requirements of the desired species and the site factors; it may also be as important to make conditions unfavorable to problem species, as to create conditions favorable to the desirable species (Ashton, 1992; Marquis, 1966). If the species that appear are more shade tolerant than those desired, it is usually necessary to increase the severity of the establishment cutting (Martin and Hix, 1988). If, for example, the existing species to be reproduced is pine, but a more tolerant species grows rapidly after shelterwood cutting, it is probably a sign that the cutting was

not heavy enough or that site preparation was inadequate (Schuler and Miller, 1995; Ray, Nyland, and Yanai, 1999). The opposite is true, if unwanted grasses or other pioneer vegetation appear. The unintended establishment of mixtures of species is usually not of concern if the desirable species outgrows the undesirable. Various indexes such as stand basal area are related to crown cover and can be used to regulate and guide the severity of establishment cuttings and thus enable transfer of experience from one case to another. Because the extraction of trees felled in the subsequent removal cuttings can cause damage to the new seedlings, it may help to take off as much of the old stand as possible in establishment cutting.

It is also useful to take advantage of all groups of advance growth that may have started naturally or as an unintentional result of past thinning. Cutting of the overstory can be much heavier in this situation, and may remove all or most of the older trees.

Removal Cuttings

Removal cuttings have the objectives of (1) gradually uncovering the new crop, and (2) taking the most merchantable trees in the overstory. There may be one or, in intensive management, several **removal cuttings**, the last of which is called the **final cutting**.

The largest and most vigorous trees usually have the greatest capacity to increase in value, and so they are the ones that are the most likely to be kept until the final cutting (Fig. 10.5). After the regeneration is established, it is desirable to watch for signs of poor growth. If the young trees develop unhealthy foliage, bend aside toward the light, or fail to maintain a satisfactory growth in height, the competition of the overwood should be eliminated or reduced. If the development of the new stand is not uniform and if there is more than one removal, it may be necessary to vary the severity of a given cutting operation in different parts of the stand area. Some patches may need full release, others may require partial release, and still others that remain unstocked may need a repetition of the establishment cutting.

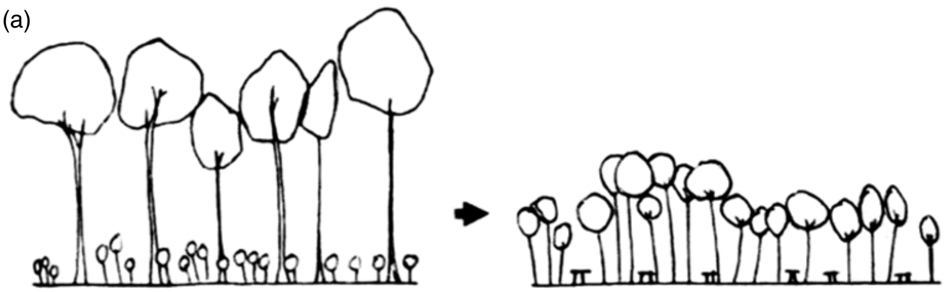
It is important to distinguish between the light conditions that are suitable for the establishment of regeneration and the light needed to make them grow in height. Establishment cuttings often provide ideal shelter for new seedlings, but much heavier removal cuttings are necessary to get them to grow well. It is important that removal cuttings open stands rapidly to allow desirable species to outgrow more tolerant competitors. After they are well established, intolerant species tend to increase in height growth with each added increment of light, right up to full sunlight, whereas the tolerant species attain a modest but maximum height growth at some intermediate light intensity. The time sequence of cuttings can range from those in which old trees are left only until the new crop is established, to those in which some of the trees of the previous crop are deliberately retained as a part of the new one. Except for the need to regulate the composition and rate of development of the new crop, there is little reason why the timing cannot be fitted to any management consideration. The spatial patterns of cutting include those in which the residual trees are scattered uniformly throughout what will become one large, even-aged stand. There may also be patterns of cutting in which trees are cut or left in strips or groups; sometimes the resulting openings are gradually enlarged in sequences of cuttings (see later in this chapter for deviations from uniform arrangements of the overstory cutting).

Because of the principle of leaving the best and most vigorous trees until the end, the shelterwood systems usually provide the best way of applying the concept of financial maturity to management of the growing stock of even-aged stands. Thus, efficient use can be made of the capacity of the better trees to increase in value without sacrificing the advantages of concentration of operations associated with even-aged management. The sequence of distinctly separate operations is more visible, more systematic, and simpler to administer than is the case with uneven-aged stands.

The removal cuttings, if uniformly applied over the regeneration area, are almost certain to cause some injury to the new stand. This injury can be reduced, but not eliminated, by care in logging. The least damage is likely to result if the overwood is harvested while the seedlings are still flexible. The greatest difficulties result when it is necessary to fell trees with broad crowns into stands of saplings. The damage usually appears more serious than it really is, and it is sometimes even a benefit in disguise. Both shelterwood and seed-tree cutting often lead to the development of grossly overstocked patches of regeneration that look fine when young, but are likely to stagnate in the sapling stage. These clumps can be crudely thinned by the skidding or felling of trees across them. It is usually best to direct the inevitable logging damage toward the densest parts of the new stand or those that are entirely unstocked, and away from the sparsely stocked portions. Many species (e.g., oaks) have the capacity to re-sprout after breakage.

If the stand consists of mixed species, then the choices are more complicated. The low-thinning principle is still important but removals might also take out large trees of species with low timber quality. However, it is also important to retain smaller trees of uncommon species for ecological purposes, such as tree species diversity. Consideration is sometimes given to reserving trees that are poor for timber but good for wildlife. The use of reserves and irregular structures is described in detail in Chapter 11.

(a)



(b)

Figure 10.5 (a) A graphic depiction and (b) a photograph of a one-cut shelterwood 15 years after treatment for Appalachian mixed hardwood forest on former Westvaco land. *Source:* (a, b) Mark S. Ashton.

Protocols for Alternative Arrangements

The uniform shelterwood progresses through the three stages (preparatory, establishment, and removal cuttings) uniformly across the whole stand. However, there are other possible arrangements when implementing shelterwoods. Three are described here: (1) one-cut shelterwood; (2) strip shelterwood; and (3) group shelterwood. There are likely other ways to accomplish shelterwood operations that have yet to be formally described.

One-Cut Shelterwood

In the **one-cut shelterwood**, the practice is very simple. If the advance regeneration is already present and well established, presumably from *de facto* past thinning operations or a natural disturbance event, then there is no reason to conduct a preparatory or establishment cutting. The operation simply includes a removal cutting, usually with one entry (Fig. 10.5). They have often been erroneously defined by foresters as a "clearcut", but this does not match its proper silvicultural definition of being lethal. A one-cut shelterwood emulates a catastrophic release disturbance where the majority of the regeneration is already in place, and does not germinate afterwards or come in from the surrounding stands. Some of the best examples of applying one-cut shelterwoods are for shade-intolerant masting species (e.g., oaks) that rely upon advance growth for their representation in a new forest stand, but that compete in the understory with slower-growing shade-tolerant species. The bottomland hardwood forests of the big river systems of the southeastern US are dominated in the canopy by the red oak species (cherrybark, nuttall, willow, and water), but have thick understories of sugarberry, elm, dogwood, and sweetgum. Simple one-cut shelterwoods are a satisfactory way of releasing the oak advance regeneration above the regrowth of the shade-tolerant trees (Bowling and Kellison, 1983; Kellison and Young, 1997; Oliver, Clatterbuck, Burkhardt, 1990; Oliver, Burkhardt, and Skojac, 2005). The system works best when the canopy removal is timed to

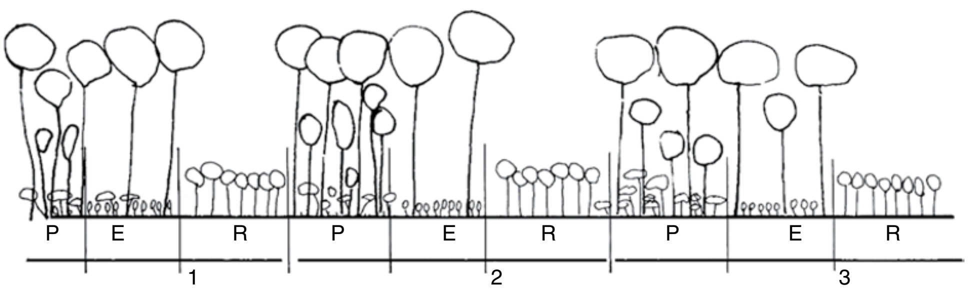
release relatively young seedlings (e.g. 1-year-old oak mast) (Oliver, Burkhardt, and Skojac, 2005).

It is very possible for early successional stands to have desirable advance growth of a later successional stage beneath them. In the Great Lakes Region, for example, red pine may follow jack pine in this manner. In New England, advance growth of maple, black birch, and oak was released from heavy timber cutting of old-field white pine at the end of the 19th century. What are seen at present in southern New England are 100-year-old second-growth, mixed-hardwood forests that originated uniformly in this manner. In another example in the Allegheny hardwood region of northwestern Pennsylvania, stands that were successively high-graded in the late 19th century built up advance regeneration beneath them. When these same stands were heavily cutover for small-dimensional materials for the wood-distillation industry in the first half of the 20th century, new single-cohort stands of mixed black cherry, sugar maple, and beech were immediately released, and grew fast and straight. Most of these cuttings were done with the pure purpose of obtaining the wood, but they were remarkably effective in the development of new uniform mixtures. Later, foresters tried to emulate this by "clearcutting" these same even-aged stands in Pennsylvania, but failed to recognize the importance of ensuring that advance regeneration was really beneath. This led to the widespread development of ferns and regeneration failure (Marquis, 1979).

Strip Shelterwood

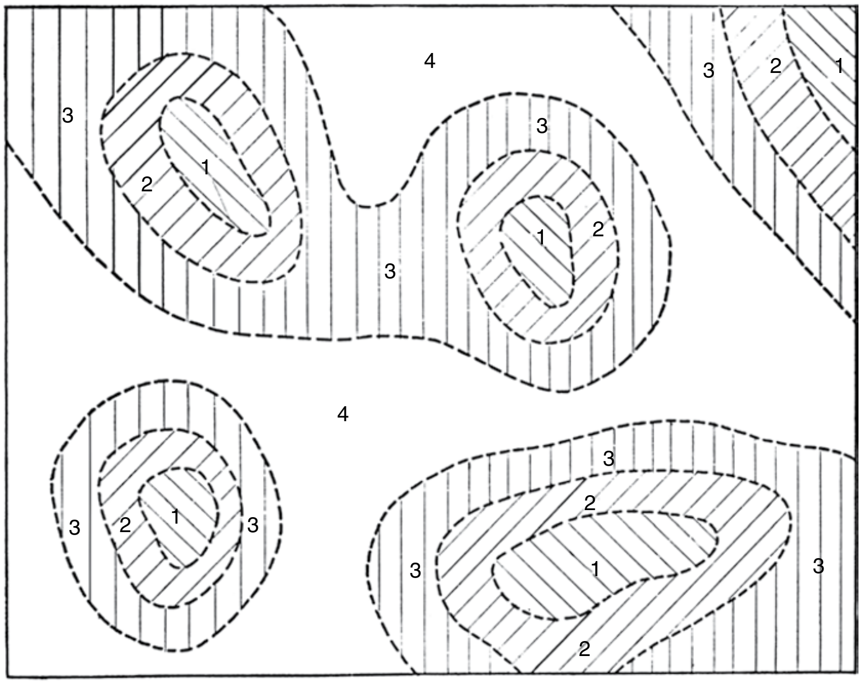
The **strip shelterwood** is more complex. It follows the same protocols as the uniform shelterwood, but the arrangement of each of the operations consists of repeating strips that are discreetly separated (Fig. 10.6). The reason for the strip arrangement is to conduct

(a)



(b)

Figure 10.6 (a) A diagram illustrating the progression of strips over time using preparatory (P), establishment (E), and removal cuttings (R). What is shown is the third entry into the stand where strips in R have been preceded by entries that have had preparatory (P) and establishment cuttings, strips in E have been preceded by preparatory cuttings and strips in P only received the preparatory cutting. **(b)** A photograph of a strip shelterwood for Norway spruce in the Czech Republic. The man is standing on the border between establishment and removal cuttings. *Source:* **(a, b)** Mark S. Ashton.



Kind of cutting	Areas marked:–			
	1	2	3	4
Preparatory and seed cutting combined	Received cuttings in years as follows:–			
		0	5	10
Removal cutting		5	10	15
Final cutting	0	10	15	20

Figure 10.7 A graphic depiction of the different sequential phases of a group shelterwood. Areas demarcated by zone 1 are where the initial preparatory cuts are done opening up the canopy to facilitate regeneration. In 5 years an area demarcated as zone 2 is opened up around zone 1 to facilitate the establishment of regeneration in zone 1 and to prepare zone 2 for seedling germination. Five years later zone 3 opens up the canopy edges further, linking gap openings and further releasing regeneration in zone 2 while starting regeneration in zone 3. The final removal of the remaining canopy in zone 4 is done after enough edge light has facilitated regeneration beneath the remaining understory. *Source:* Yale School of Forestry and Environmental Studies.

shelterwoods in stands that are on slopes susceptible to erosion, or riparian areas susceptible to flooding, or exposures and aspects susceptible to windthrow. In all of these circumstances, the use of strips to counter prevailing winds, tidal or river inundations, or surface soil erosion, is an effective technique of following the shelterwood protocol in order to secure new advance regeneration at the same time as protecting the site. The strips are advanced progressively in a direction such that the timber extracted for the creation of each strip during the establishment and removal cuttings is extracted in a way that it does not cross areas of regeneration. Sometimes the strips are advanced from leeward to windward against the direction of the most dangerous storm winds.

Group Shelterwood

The third and last arrangement is the **group shelterwood** method. The mode of operation is to start in particular areas with preparatory and/or establishment cuts that create appropriately sized canopy openings suited to the shade tolerance of the regeneration being established. These openings are then sequentially expanded upon over a relatively short period, relative to the rotation (e.g., 20 years over a 100-year rotation), such that gaps finally merge and link with each other (Figs. 10.7 and 10.8). Group shelterwoods are appropriate to implement in a number of situations. An obvious example is where regeneration has already been established but in particular places, perhaps from past cutting. This provides a good opportunity to utilize these patches that can then be released and expanded upon. A second example is to use the topography and differences in soils as a guide, particularly if it is undulating with variations in drainage and fertility. The method can focus on establishing regeneration where it is easiest, and then to move back into areas that are more difficult, using the established regeneration as a medium and edge for support of new smaller establishing areas.

(a) (b) (c) (d)

Figure 10.8 Photographs depicting **(a)** preparatory and **(b)** establishment phases for a group shelterwood in European beech stands in the Czech Republic, and **(c)** preparatory and **(d)** establishment phases in Norway spruce–silver fir in Bavaria, Germany. *Source:* **(a, b)** Mark S. Ashton. **(c, d)** Yale School of Forestry and Environmental Studies.

Application of Shelterwood Methods

Shelterwood regeneration methods have many more variants and wider applicability than seed tree and true clearcutting. Within the framework of the shelterwood, there can be a variation in the relative degrees of shelter and exposure in both space and time. Adjustments can be made to meet the requirements of almost all species except those that are exceedingly intolerant of shade and root competition. They are the most inclusive of the even-aged methods of regeneration and can be applied to very sophisticated modes of harvesting compatible successional crops (Fig. 10.9)

Shelterwood methods simulate the effects of windstorms and similar disturbances on large trees that kill forests from the top down, and release small trees of species adapted to start as advance regeneration. The term "shelterwood" denotes one purpose succinctly: sheltering seedlings. However, like the seed-tree system, the shelterwood method is employed to distribute seed from parent trees that have poor or unpredictable dispersal agents, and to maximize the productive capacity of the growing stock by allowing the best trees to grow larger. Applications of shelterwoods are presented for the following range of forest and tree types: conifers, oak hardwoods, northern hardwoods, and tropical hardwoods.

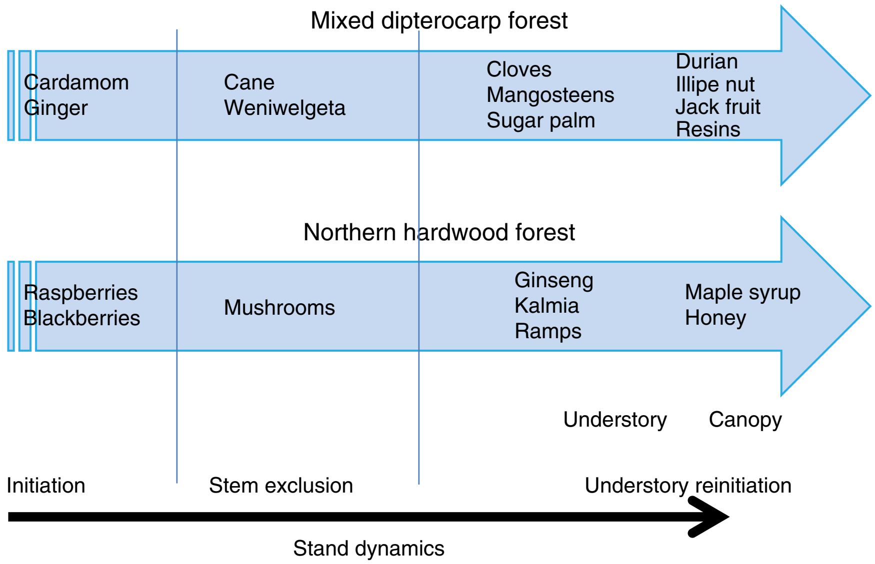


Figure 10.9 Shelterwoods can be the most inclusive natural regeneration method for complex mixed-species stands, in particular where the most shade-tolerant species rely upon advance regeneration. By including multiple species in the successional cycle, the opportunity exists of harvesting many products from trees that mature over the course of stand development ending with the timber trees. Adding all tree and non-timber species together increases the net present value of a stand by compatible stacking as compared to management for timber alone. A graphic illustration is shown for shelterwoods as sequentially successional cropping systems for non-timber forest products in a mixed dipterocarp forest from tropical Asia and a northern hardwood forest from northeastern North America. *Source:* Mark S. Ashton.

Shelterwood Methods for Conifers

The Hard Pines

The most common American use of shelterwood cutting for the regeneration of pure stands is for conifers, especially for many pine species. Though it is not widely practiced at present, it has been used successfully for loblolly and shortleaf pines, when coupled with adequate control of hardwood competition (Baker and Balmer, 1983). It is regarded as a good way of regenerating longleaf pine, which is difficult to plant and has very slow-growing seedlings (Boyer 1993). When ponderosa pine is grown using even-aged management, the regeneration is often accomplished by shelterwood cutting. In the case of the Black Hills of South Dakota, which have summer rainfall and abundant regeneration, stand management is fairly easy. In other parts of the rather large, arid range of ponderosa pine, it may be necessary to wait patiently and practice something that is between a seed-tree and a shelterwood method, in order to reduce the belowground competition for water between establishing seedlings and the groundstory shrubs. Red pine has also been successfully managed under the uniform shelterwood system, although it has been difficult to achieve prompt regeneration (Benzie, 1977; Benzie and Alm, 1977).

The Soft Pines

In the case of the moderately shade-intolerant sugar pine, eastern white pine, and western white pines, the shelterwood is advantageous for pest management and ideal for establishment of natural regeneration. For all the soft pines, the establishment cut must be severe enough to allow the pine seedlings to grow faster than their more shade-tolerant competitors, such as hemlock and fir (Box 10.1).

The main problem with growing eastern white pine is the white pine weevil (Funk, 1986). This insect often kills the terminal shoots of the trees when the tops are in the sunshine. The replacement branches are usually the laterals of the previous year, and when they turn upward, they form a crook that badly deforms the stem. One solution is to use a shelterwood overstory (older white pine or other species) to keep the young stems shaded until at least one log-length has formed (Fig. 10.10). Older white pines provide the best shade because the weevils are lured away to their sunlit crowns.

With western white pine, the introduced blister rust is the major problem. Shelterwood cutting plays a role by keeping the understory *Ribes* shrubs in-check. The *Ribes* shrub is the alternate host of the rust fungus, so the control of the *Ribes* will reduce the tree damage. The partial shade from shelterwood cutting is fine for pine seedlings, but that level of shading is too much for *Ribes* to survive and produce seeds.

Douglas-Fir, True Firs, and Spruces

Douglas-fir and many other conifers of western North America are ecologically well adapted to shelterwoods (Williamson, 1973; Seidel and Cooley, 1974; Seidel, 1983; Burton *et al.*, 2000). In the past, the use of the method did not develop because of the difficulties of partial cutting, especially in ancient unstable stands and on the steep terrain that is so common. On private lands in such

Box 10.1 Regenerating the mixed conifer stands of the Sierra Nevada Mountains of California by use of shelterwood.

Introduction

There are five conifers and one hardwood that make up this mixture. This includes California black oak, ponderosa pine, Douglas-fir, incense-cedar, sugar pine, and white fir. These species dominate the middle elevations in the northern Sierras but gradually increase to high elevation on progressing south. All are killed by lethal crown fires, but white fir, the only thin-barked species of this mixture, is also susceptible to ground fires, as is sugar pine to some extent. White fir is the most shade tolerant followed by sugar pine, incense-cedar, Douglas-fir, ponderosa pine, and black oak.

Regeneration

To satisfactorily regenerate the complete mixture, it is best to focus on sugar pine. Sugar pine is intermediate in shade tolerance but has the most irregular masting events (every 3–5 years) and seeds do not disperse far from the parent tree. Black oak also has poor seed dispersal. All tree species require mineral soil for best seed germination. White fir is the most prolific seed producer. Shelterwoods are therefore designed with a preparatory cutting to take out much of the fir, followed sometimes by a surface fire to prepare the seedbed. Several years later the establishment cut can be done to space the canopy pines and fir, and to provide intermediate to low shade. Enough trees (12–20/acre; 30–50/ha) are needed to promote sugar pine dispersal, but spacing needs to allow enough light to promote the shade-intolerant ponderosa pine, incense-cedar, and Douglas-fir (Fig. 1). The number of shelterwood trees increases and their spacing decreases in relation to aspect (south versus north) and on progressing south in the Sierra.

Box 10.1 Figure 1 A shelterwood establishment cut in a mixed conifer stand leaving 20 trees/acre on the Stanislaus National Forest in the Sierra Nevada. Slash was piled and burned as a site preparation. *Source:* Mark S. Ashton.

places as western Oregon and Washington, the climate and soils are favorable for clearcutting and planting as a dependable solution. Shelterwood cutting may be used to meet goals on public lands that require more structural and compositional diversity, but partial shade is not necessary for regeneration.

Most of the region is so mountainous that elevation differences and rain-shadow effects create intricate patterns of variation in site factors to which silviculture must be adapted. One locality where shelterwood cutting seems desirable is southwestern Oregon, which has rainless summers. The problem sites include south-facing aspects, coarse-textured soils derived from granite, and low rainfall. On these sites, partial shade reduces both direct evaporation and extremes of surface temperature, enough to allow seedlings to become established from natural regeneration. In addition, the shade may reduce the establishment and spread of *Ceanothus* and manzanita shrubs, which are aggressive and can easily exclude young trees.

At high elevations, both incoming solar radiation by day and outgoing radiation by night are so great that extremes of surface temperature are very wide. They are so wide that high-elevation spruce–fir, particularly on southern aspects, are better regenerated naturally through the use of shelterwoods. However, on cool, moist northern aspects, advance regeneration can build up such that a one-cut shelterwood can work well (Ferguson and Adams, 1980).

Figure 10.10 A shelterwood establishment cutting in a 74-year-old stand of eastern white pine in the Pack Forest in eastern New York. The establishment cutting was carried out 12 years prior to the photograph. The overstory is being used to reduce damage to the crowns of the seedlings from the white pine weevil.
Source: Yale School of Forestry and Environmental Studies.

Shelterwoods are very suited to the spruce–fir forests of the northeastern maritime provinces of Canada and Maine (Seymour, 1992) as well as the forests of southwest Alaska (Greene *et al*., 1999). In Quebec, red spruce and balsam fir regeneration grew best with establishment cuts that removed about 60% of the initial basal area (Pothier and Prevost, 2008). In Scandinavia, as could be predicted, birch (*Betula pendula* and *Betula pubescens*) is negatively associated with amount of shade, while survival and establishment of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) were unaffected. To secure Norway spruce and Scots pine, Nilsson *et al.* (2002) recommend a canopy cover that provides partial shade (25% of initial basal area) with a soil surface that is lightly scarified to expose some of the mineral soil and encourage decomposition of organic soil.

Shelterwood Methods for the Eastern Upland Oak–Hickory Forests

Oaks are one of the most important groups of trees in eastern North American forests both in their economic and ecological value. However, assuring their regeneration through management in new forests is difficult. Most of the oak forests are a legacy of past land use. They have a history of land abuse from fire, subsistence agriculture, fuelwood, and timber cutting. Oaks flourished under these circumstances because their seed had few predators. Voles, mice, squirrels, deer, turkey, and jays were all rare because of hunting or because these animals are forest dependent and little forestland existed at that time. Oak seedlings survive surface fires, sprout vigorously, and can withstand dry open conditions (Box 10.2). Current oak stands are a main source of food for many species of wildlife, and prior to land colonization and clearance, to people as well. These forests are very different now, compared to the conditions when the oak forests arose. Now there is strong fire protection and an absence of fire on the landscape. Predators of acorns are in high numbers because forestland conditions have returned and hunting pressures are low. Fire protection has led to the rise of a more shade-tolerant, moisture-loving species assemblage (maples, black birch, yellow-poplar, sweetgum) that outcompete oak in securing space in the understory for advance regeneration. It is no wonder that trying to regenerate these forests is difficult. However, the ability to regenerate oak varies dramatically, based on site, species competition, and seeding phenology.

On drier soils and/or climates with lower continental rainfall, the more shade-tolerant moisture-loving competition is absent. Oak seedlings can establish and build up numbers that can stay in the understory for many years. All that is needed is for the forester to recognize the presence of advance regeneration on these kinds of soils. It is simplest and easiest to treat this as a one-cut shelterwood (Hannah, 1988). However, these are the very sites that should be held on to, to provide more overwood and structure for ecological or wildlife habitat purposes, because of oak's superiority at holding on to its growing space in these conditions, relative to competition from other species.

On the lower slopes and deep moist soils, or in climates with higher rainfall with more maritime influences, the oak forests that arose a century ago from past land use are much more difficult to replace. This is primarily because of competition, both during the periods of time when advance regeneration is establishing in the understory, and post-disturbance competition of what regeneration has established with other faster-growing, more shade-enduring species. A study done in southern New England (Frey *et al*., 2007) showed that although masting events are fairly periodic, once every 3–4 years (Healey, Lewis, and Boose, 1999), actual successful seedling establishment in large cohorts within the forest understory is much less frequent (once every 10–15 years). This is complicated by the fact that on moist sites, 99% of this regeneration is dead after only a few years because of the greater canopy shade. On drier sites, high percentages have been recorded to survive longer than 20 years (Ashton, unpublished data). The establishment cut for oaks in northern

Box 10.2 The importance of seedling sprouts for regenerating oak, hickory, and other heavy-seeded nut species.

Sprouts that come from the base of small saplings and seedlings after injury (e.g., fire, browse) usually have the same anatomical and physiological origin as stump sprouts, but they also have so many attributes of seedlings that they are called **seedling sprouts**. They are defined as coming from stumps less than 1 in (2.5 cm) in diameter. This generally means that the stumps may have only sapwood and may quickly be covered over with callus tissue. Both factors greatly reduce the risk of heart-rot spreading from stump to sprout. They are considered a form of vegetative reproduction (see Chapter 12) but they are in and of themselves of seedling origin. However, they are superior to seedlings as sources of regeneration because the new shoots grow more rapidly as the result of having established root systems to nourish them. The stems tend to be straighter simply because the faster a tree grows through a certain zone of height, the less time there is for the operation of agencies that create deformities (Fig. 1).

Although almost any sprouting species can produce seedling sprouts, they are especially important with many large-seeded species such as the oaks, hickories, chestnut, and walnuts. All these species would be classified as long-lived later successional trees that are also intermediate intolerants of shade (see Chapter 5; Fig. 5.6). The seedlings of these species are seldom extremely numerous, but once established, they are very persistent and may survive for many years in the partial shade of older trees. The seedling tops continually grow up and get killed back from browsing, groundstory fires, and shade, but the carrot-like roots often survive and grow larger. When some permanent release takes place, these kinds of plants grow rapidly; they often are a chief source of regeneration for the species involved. The mechanism enables a kind of long-term storage of advance growth, especially of species that produce small numbers of large seeds. These species are therefore ideal candidates for the shelterwood method of regeneration. Studies have also documented successful oak regeneration following seed-tree and selection methods of regeneration. All of these regeneration methods would require treatments to secure their established presence before canopy removal.

While large parent-tree stump sprouts for these species can provide competitive vegetative regeneration, they are often too sparse to substantially contribute to a future stand's component, and sprouts decline in both number and vigor with the size of tree cut. The importance of advance regeneration of these species (especially oak and hickory) is well documented for a range of treatments, site indexes, and forest types. There are significant variations in the competitiveness of oak and hickory on different sites and in different forest types. For instance, xeric sites often have much more oak advance regeneration because the seedlings have greater amounts of understory light available and less competition from other species, allowing cohorts to accumulate after successive mast years. On more mesic sites, the presence of advance regeneration is tenuous as the lack of light causes high seedling mortality as compared to xeric sites where their die-back re-sprout abilities are much stronger.

Box 10.2 Figure 1 Two-year-old white oak seedling sprouts. *Source:* H. Lewis, New Hampshire State Forest Nursery. Reproduced with permission from New Hampshire State Forest Nursery.

hardwood stands is complicated because of the large number of tree species. A method for determining percent crown cover for marking trees has been made (Leak and Tubbs, 1983), using diameter at breast height (DBH)/crown cover data for the 10 main tree species.

To successfully regenerate oak on the moister soils and in wetter climates, shelterwoods are an obvious method to use. However, the regeneration often needs to be present before the establishment cutting because studies have shown it will not significantly increase afterward (Sander, 1979; Johnson, Shifley, and Rogers, 2009) (Box 10.3). Again timing is critical with best establishment often related to the release of advance regeneration that is only a year or two old.

Box 10.3 Regenerating oak on sites with shade-tolerant competitors in New England and the Appalachians.

Introduction

Tree species differ in their competitive ability at different sites due to physiological and morphological characteristics. As a result, silvicultural treatments can have varying degrees of regeneration success depending on site quality. In the oak–hickory forests of the southern Appalachians and southern New England, variation in competitive ability of northern red oak (*Quercus rubra*) is addressed by adjusting shelterwood basal area reductions across site gradients and developing site-preparation treatments that favor oak compared to more shade-tolerant hardwoods.

In southern Appalachian forests, one of the primary competitors of northern red oak is yellow-poplar (*Liriodendron tulipifera*). Yellow-poplar competes well on high-quality mesic sites. In southern New England, black birch (*Betula lenta*) often out-competes northern red oak on mesic sites. Yellow-poplar and black birch are similar in that they are both considered intermediate shade-intolerants that can produce rapid growth compared to red oak, which is also considered an intermediate shade-intolerant (see Fig. 10.1). Neither birch nor poplar have as large a seed or allocates as many resources to seedling root development as northern red oak does.

These physiological differences confer competitive advantages to the different species on different sites. On low-quality sites, the developed root system of advance regeneration northern red oak can provide the seedling with more moisture and nutrients than either yellow-poplar or black birch and it holds a competitive advantage. On the other hand, on more shaded mesic sites, moisture and nutrients are more readily available, and the developed root systems of advance-regeneration oak do not confer an advantage. The silviculturalist must therefore make use of differences in shade tolerance to favor one species over another and meet regeneration goals.

Regeneration

In the USFS Bent Creek Experimental Forest in Southern Appalachians, David L. Loftis has developed basal area reduction guidelines for naturally regenerating northern red oak in shelterwood treatments. Mature fully-stocked stands are reduced to 60%, 65%, and 70% of initial basal area where oak site index is 70, 80, and 90 feet, respectively. Before cutting, herbicides should be applied in a preparatory treatment by stem injection to saplings and poles of shade-tolerant competitors. After the preparatory herbicide treatment, an establishment cutting reduces basal area from below. This can be followed up afterwards with herbicide, applied using the cut-stem method to the base of trees such as red maple and yellow-poplar to stop the sprouting. Overstory removal takes place 10 years after the treatment to allow for advance-regeneration oak to increase basal diameter and competitive ability (Loftis, 1983, 1990).

Research at Yale Myers Forest in southern New England on seedling dynamics (recruitment and survival) has informed shelterwood spacing across topographic gradients related to moisture. Spacing of canopy trees ranges from 30–45–60 ft, as a forest moves from xeric ridges, to intermediate slopes, to very mesic toe slopes. Shelterwood spacing is wider on more mesic sites to promote the relatively shade-intolerant northern red oak over the more shade-tolerant yellow-poplar and black birch.

Additionally, prescribed burns following shelterwoods have been shown to favor growth of northern red oak. In

Box 10.3 Figure 1 A typical understory of an Appalachian oak hardwood forest prior to a shelterwood. *Source:* US Forest Service.

Box 10.3 (Continued)

Box 10.3 Figure 2 Regeneration release of vigorous yellow-poplar regeneration after the establishment cut of a shelterwood. *Source:* US Forest Service.

Box 10.3 Figure 3 A prescribed burn treatment to the advance regeneration kills the yellow-poplar and promotes re-sprouting of the fire-tolerant oak beneath. *Source:* US Forest Service.

the central Appalachians of West Virginia, high- to medium-intensity spring or summer fires can reduce yellow-poplar dominance (Brose, Van Lear, and Keyer, 1999; Brose, 2010). Fire is not used to secure oak regeneration but to release it after the canopy has already been opened (Brose and Van Lear, 1998; Brose, Van Lear, and Cooper, 1999; Brose, Schuler, and Ward, 2005) (Figs. 1, 2, 3). Prescribed fires take advantage of the greater fire tolerance of oak relative to yellow-poplar or black birch, which experience higher mortality during fires and do not resprout as vigorously as northern red oak. The legacy of the single-burn treatment remained effective in releasing the oak and hickory from the competition with poplar and red maple at least 10 years later (Brose, 2010; Brose, Schuler, and Ward, 2005). Similar studies have been done in New England with mountain laurel, an evergreen shrub in the rhododendron family, but in this case the laurel sprouts back with the oak. If the burn is done after the establishment cut, the oak overtops the laurel sprouts; if the burn precedes the establishment cut, the more shade-tolerant laurel overtops the oak (Moser, Ducey, and Ashton, 1996).

Shelterwood Methods in the Northern Hardwoods

The northern hardwoods extend across North America's northeastern states, from Minnesota to Maine and from south central Canada (Ontario, Quebec) south along the Appalachians. The soils are mostly glacial and the climate is cold and moist. The dominant species include sugar maple, red maple, black cherry, beech, white ash, yellow birch, and paper birch. Eastern hemlock is the single most important conifer associated with northern hardwood. Natural disturbance regimes that renew forests range from convectional windstorms, ice storms, and occasional tornadoes, to small single-tree windthrows, droughts, and insect defoliation. Most of these forests have had a sequential series of high-grading for the best timbers during colonization, with the advancement of the frontier from east to west (1700–1850). This was followed with heavy removal cuttings for firewood, charcoal, and the wood chemical industry, during the industrial revolution (1850–1920). Across the whole region, the new forest is now mostly even-aged of 70–100 years. Unlike the oak–hickory forest, most of this forest was never cleared for agriculture and then abandoned. Its history is one of exploitation and cutting, with the subsequent release of advance regeneration. Forests that were completely cleared for pasture and agriculture went through an old-field conifer stage, after which advance regeneration became established and then eventually formed new second-growth stands.

The shelterwood is the regeneration method most suitable for the current forest structure and species composition. For the Lakes States region, Godman and Tubbs (1973) recommend two fellings for stands older than 40 years; stands that are younger and reproductively immature are difficult to regenerate by seed-origin natural regeneration. The establishment cut should remove about 40% of the initial stand basal area. To increase the yellow birch component, the proportion of basal area should be higher, the soil should be lightly scarified, and there should be some vegetative control of the beech and maple. In the Allegheny region, Marquis (1979) recommended removal of 33% of the basal area to encourage black cherry in 50–70-year-old stands, and that the overstory should be removed after 5–10 years. However, because of high deer populations, fern and grass cover can increase on poorly drained soils, creating potential interference with the seedlings; these problems need to be controlled by foliar application of herbicide (Horsley, 1994).

For the Adirondack region, the most appropriate establishment cutting to favor sugar maple and yellow birch required stand removal down to 50 ft^2/acre (11.5 m^2/ha) of residual basal area in areas that had controlled deer densities below 14 deer/$mile^2$ (36 deer/km^2), and where understory beech had had a preparatory cutting with a cut-stem application of herbicide (Kelty and Nyland, 1981). Total stem numbers peaked about 5 years after the establishment cutting and by 10 years, closed-canopy stands were rapidly self-thinning (Ray, Nyland, and Yanai, 1999). Removal cuttings should be completed by year 10. In the silvicultural guide to northern hardwoods for New England, Leak, Soloman, and DeBald (1987) suggest an establishment cutting that leaves 50–80 ft^2/acre (11.5–18 m^2/ha) with a removal cut 5–10 years afterward. This kind of treatment would provide a high proportion of shade-tolerant species in the regeneration, with sugar maple on the more fertile, higher pH soils, and beech on the poorer more acid soils. Higher deer densities promote beech and striped maple over sugar maple and white ash. Leaving lower residual basal areas of 20–40 ft^2/acre (4.5–9 m^2/ha) promotes more yellow birch. In addition, a method for determining the establishment cut for New England has been devised, based on data for tree DBH and crown cover (Leak and Tubbs, 1983). The removal cut is best done when the ground is frozen and the snow can protect the regeneration.

Shelterwood Methods in Tropical Rainforests of Southeast Asia

The mixed dipterocarp forest type dominates the southeast Asian wet evergreen rainforests. Like the oak–hardwood forests of eastern North America, these rain forests are dominated by one very species-diverse family of trees, the Dipterocarpaceae. Once widespread across the region, most of these forests in the lowlands have been selectively logged and converted to other land uses such as rubber and oil palm. There was a period of time during the heaviest exploitation (1960–2000) that dipterocarps comprised the largest volumes of timber traded on international markets in the world.

Shelterwood systems in mixed dipterocarp forests of southeast Asia have a long colonial history of development. Many dipterocarps exhibit masting, are relatively shade intolerant (red meranti type), and are site restricted, creating relatively simple mixed-species stands, with standing merchantable volumes of timber greater than 1400 ft^3/acre (100 m^3/ha). These forests are suited to uniform shelterwood treatments, where preparatory treatments are focused on establishing advance regeneration of the shade-intolerant canopy trees prior to canopy removals. Mixed dipterocarp forests can range in merchantable timber volumes from a low of 350 ft^3/acre (25 m^3/ha) on infertile or drought-prone ridge sites, or low-lying hydric swamps, to a high of over 2860 ft^3/acre (200 m^3/ha) on fertile lowlands (Nicholson, 1979; Bertault and Sist, 1997; Ashton *et al.*, 2001). This

contrasts with the mahogany-rich forests of Africa and South America, where volumes of commercial timber rarely exceed 570 ft^3/acre (40 m^3/ha) when averaged across a large forest area (Verissimo *et al*., 1995; Barreto *et al*., 1998; Sist and Nguyen-The, 2002).

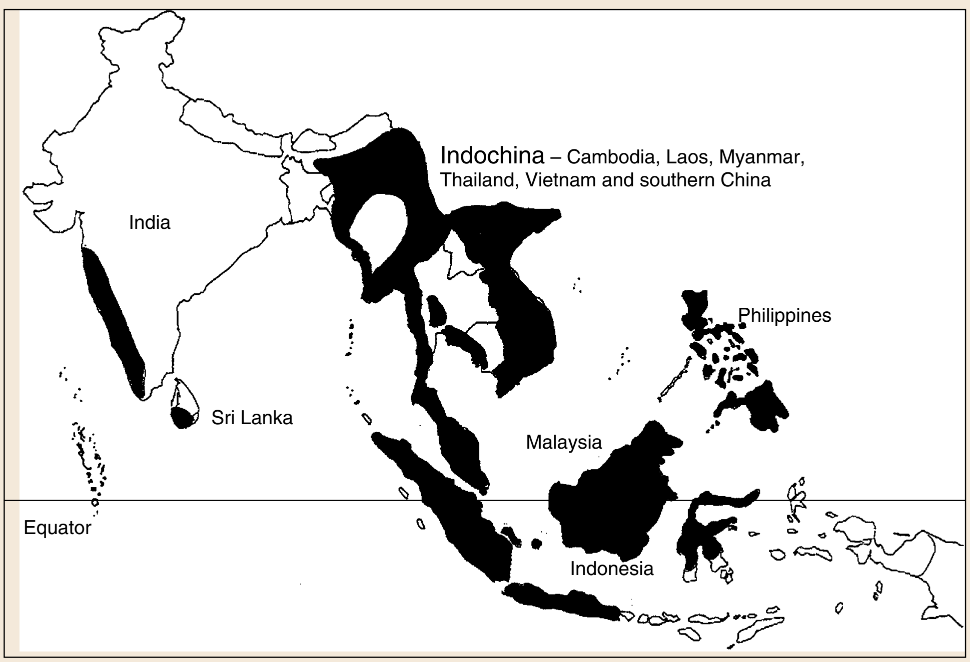
Simple systems that were developed for the Asian mixed dipterocarp forests were first successfully implemented where advance regeneration was easily secured, or where it was almost always present before any treatments were made. These conditions tended to be restricted to the lowland mixed dipterocarp forest types. The Malay Uniform System was developed as a one-cut shelterwood for forests dominated by *Shorea leprosula*, *Dryobalanops aromatica*, and other red meranti associates (Box 10.4) (Wyatt-Smith, 1963). In other lowland dipterocarp forests of South Asia, seed-tree systems for *Dipterocarpus zeylanicus* were developed (Holmes, 1957) and for forests comprising moist sal (*Shorea robusta*) in Uttar Pradesh, India one-cut shelterwoods were used (Joshi, 1980). These systems worked primarily because they were applied to forests which were dominated by one or two shade-intolerant dipterocarp species that mast and regenerate prolifically. Much of this kind of forest has now been cleared for agriculture (oil palm, rubber) and only fragments remain.

More complex shelterwood systems have been developed following uniform shelterwood protocols, but leaving various kinds and arrangements of reserves that create two or three age-class systems (multiple-aged). These will be described in further detail in Chapter 11.

Box 10.4 The Malaysian Uniform System.

Introduction

Mixed dipterocarp forest once dominated the lowlands of Malaysia (Fig. 1). This forest type comprised many timber species in the genus *Shorea* (Dipterocarpaceae). In particular, the forest type at this elevation was composed of *Shorea* species that had prolific masting, and seedlings that were present as advance regeneration in the forest understory. The most obvious timber tree that represented these traits was the light meranti *Shorea leprosula*. Research in the 1920s by researchers within the newly founded Forest Research Institute in Kepong, Malaysia, suggested that the best way to regenerate this kind of forest was a form of one-cut shelterwood. The method is summarized from years of work done at that time by Wyatt-Smith (1963) in his book *The Manual of Malayan Silviculture for Inland Forests*.



Box 10.4 Figure 1 A map depicting the original range of mixed dipterocarp forest in tropical Asia. The black depicted in the map is lowland and hill mixed dipterocarp forest. This forest type dominates climates with high rainfall areas throughout southeast Asia. *Source:* Mark S. Ashton.

(*Continued*)

Box 10.4 (Continued)

Box 10.4 Figure 2 A young stand of mixed dipterocarps in stem exclusion 25 years after regenerating by the Malaysian Uniform System at Sungei Menyala, Malaysia. Note the uniformity of the pole-sized stems. *Source:* Mark S. Ashton.

Regeneration

The Malayan Uniform System (MUS) prescribes the removal of all trees greater than 45 cm (18 in) DBH in a single cutting followed by a liberation release treatment (see Chapter 20) that girdles and poisons all remaining non-commercial trees that remained in the overstory down to 15 cm (6 in) DBH. Approximately 2–5 years after cutting and subsequent release, an inventory is carried out to determine the stocking and status of the regeneration and to decide whether further release treatments are necessary. The MUS has been applied successfully to the lowland dipterocarp forests (see Fig. 2) but is unsuitable for the hill mixed dipterocarp forests for a number of reasons. The slopes are steeper and sensitive to erosion, the stocking of the timber trees themselves is irregular, the presence of advance regeneration in the understory is both erratic and established from more irregular masting and seed-production events, and lastly the presence of the understory stemless palm (*Eugeissona triste*) shades out any potential to establish in the understory.

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11

Natural Regeneration: Irregular Seed-Tree and Shelterwood Methods (Multi-Aged Systems)

Introduction

The creation of forest stands with **two- or three-aged structures** (multi-aged) has been a part of silvicultural practice for many centuries, but was used only in very limited situations for most of that time. Many books on silviculture (including earlier editions of this textbook) did not include this practice in any detail because it was so rarely used. More recently, widespread interest has developed in creating these kinds of stands, particularly in regions where clearcutting and planting single-species plantations had become a common practice. New methods are now desired for improving habitat conservation and landscape appearance within silviculture (O'Hara, 2001). These new methods were created largely because of the size and number of clearcuts, especially with Douglas-fir in Washington, Oregon, and British Columbia, redwood in California, and spruce in Ontario and Quebec. However, it is important to recognize that the new methods adopted in the western US and Canada are a hybrid system where structure and multiple age classes are left behind, but planting is still the norm. These methods are not natural regeneration methods but are variants of plantings described in Chapter 16. Some of the current changes were made because of national-scale controversies about timber harvesting, beginning in the 1980s. The methods described in this chapter are partly in response to a concern about habitat and landscape issues, but most of them are old methods that are being brought back into current silviculture.

Two- or three-aged stands are created by retaining a portion of the prior cohorts of mature stands while harvesting the majority in order to establish a new age class. Immediately after this harvest, the stand structure is often similar to that which follows a uniform, single-aged, seed-tree cut or a shelterwood cut. Two- or three-aged systems can therefore be defined as either seed-tree or shelterwood (see Chapters 9 and 10 respectively) by their focus on the type and origin of regeneration. However, they are further defined as **irregular**, meaning that, although the protocols for securing regeneration are the same as seed-tree or shelterwood, the retention of additional structures and age classes makes them spatially more heterogeneous. By implication, although there can be up to three age classes, they are distinctly **unbalanced**, with the most recent regenerating age class dominating the number and spatial area of the stand. The long-term development of the stand differs from uniform seed-tree and shelterwood systems in that the mature trees are retained (or **reserved**) for a substantial period, while the new age class grows up around them. In most cases, these mature reserve trees would be kept in the stand for the entire rotation of the younger age class. This is in contrast to a uniform or regular seed-tree cut or shelterwood cut, where the overstory would be removed 5–30 years after the initial cut. However, where at least four, or usually more, age classes are **balanced** (or relatively so) in distribution throughout the stand area, the system would be defined as all-aged, and also as a selection system (see Chapter 13).

Two- or three-aged silvicultural systems are used to meet several objectives.

- **To retain habitat elements of a mature forest**. Forest structure is partially maintained to provide habitat for plants, animals, fungi, and microbes that are adapted to mature forest conditions.
- **To maintain a portion of the mature forest for its aesthetic, religious, or cultural value**. The visual impact that accompanies the final harvest in an even-aged system is reduced by retaining mature trees on the site.
- **To reserve a set of trees of good timber quality.** Very large or slow-growing timber trees can be left for twice the length of the usual rotation.

In most cases, reserve trees serve more than one of these objectives. Concerns for aesthetics and habitat have been at the forefront in recent years, but in some cases, the protection of cultural trees or provisions for producing large sawtimber trees have also been instrumental in the renewed interest in two- or three-aged structures.

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

Development of Two- or Three-Aged Stands

The defining characteristic of stands with two- or three-aged structures is a set of mature overstory trees intermixed with a younger age class. Mature canopy trees generally slow in their height growth as they age, and in some species they cease height growth almost entirely. In a two-aged stand, young trees grow much faster in height than mature canopy trees, so the younger trees can reach the canopy layer when they are still young. It may be difficult to estimate differences in tree age by comparing heights, but the larger stem diameters and crown areas will show a substantial difference between old and young trees (Fig. 11.1). Two- or three-aged stands are created by catastrophic stand-replacing disturbances caused by wind or fire, or from prior agricultural land-use histories where legacy trees (also known as wolf trees) still prevail. Stands that had been high-graded also have this structure, if most of the trees are cut except for the few poor-quality stems. Three-aged stands are very common in eastern US forests because, in the history of these forests, mature second-growth forests are now being regenerated. Foresters have the choice when they establish a new cohort, for leaving reserves of this second growth, and reserves of the legacy trees from the original pastures and old fields that the second growth grew around. Nature can repeat this kind of age-class distribution in flood-, fire-, and wind-driven episodic disturbances that re-occur at long time intervals in the mixed coniferous forests of the west (fire) and in the hardwood forests of the east (floods, wind).

Regeneration Methods Including Reserve Trees within Irregular Seed-Tree and Shelterwood Systems

The regeneration methods leading to two- to three-aged stands can most easily be thought of as modifications of single-aged methods of clearcut, seed-tree, and shelterwood. An important advantage of two- or three-aged methods is that they provide some of the habitat and aesthetic benefits associated with uneven-aged/all-aged methods, but keep much of the management efficiency of even-aged methods. The logical terminology for two- or three-aged regeneration methods is based on the even-aged methods (Helms, 1998): **seed tree with reserves**, and **shelterwood with reserves**. On occasion, there can be the opportunity of conducting a **true clearcut with reserves**.

For the true clearcut with reserves method, there is a single regeneration cutting, leaving only the reserve trees. These reserves do not serve as a seed source in any way, by definition, but solely as a habitat structure. They must be few in number, so as not to shade the ground-story germination environment for the newly establishing pioneers. One example would be the use of snags as reserve structures in clearcuts. For the seed-tree with reserves method, the harvest removes the entire stand except for both reserve trees and seed trees. After regeneration has been established, the seed trees can be removed (as is usual with the seed-tree method), leaving only the designated reserve trees. In some cases, the seed trees may also serve as the reserve trees, so there is no need for a removal cut. In that case, it is important that the reserve trees be chosen so that they are of the appropriate species, vigor, number, and spatial distribution to establish the required regeneration. For the shelterwood with reserves method, more complicated planning may be required because the residual stand may need to provide for all or most of the following: appropriate density for shading, production and dispersal of seed of desired species, continued growth of valuable trees to be harvested in the removal cut, and retention of trees to be left as the eventual reserve trees.

The use of reserve methods has helped in meeting the interests of forest owners, conservationists, and the public, dealing with somewhat improved landscape quality and forest habitat structure. Many forest managers have been using the reserve methods. However, the use of reserves is often undertaken only because they are required to use them. Many of the operations using clearcut with reserves have been used only because of a government mandate. For example, the Oregon Forest Practices Act requires that the harvesting must leave at least two snags or green trees at least 30 ft (9 m) tall, and 11 in (28 cm) diameter at breast height (DBH), with 50% of these being conifer for each acre (ha) harvested, and two downed logs or downed trees. Many US western states and Canadian provinces have these kinds of requirements. Also, some forest companies leave substantial numbers of standing timber trees after a harvest (without being required to do it) in order to reduce negative feelings of the public about the cutting operation and the company in general. However, it should be clear that these operations are **not** silvicultural practices. A silvicultural plan would include the current regeneration method (operation) and also the future treatments.

An old term that was used to describe two-aged regeneration methods was **high forest with reserves**. High forest with reserves is an appropriately broad term that indicates that the regeneration harvest might be a modification of any of the high forest (non-coppice) even-aged methods. This term is the basis for the three names used above (e.g., true clear cut, seed-tree, shelterwood), which specify the even-aged regeneration method used. As the method has been re-invented for various purposes and forest types in recent decades,

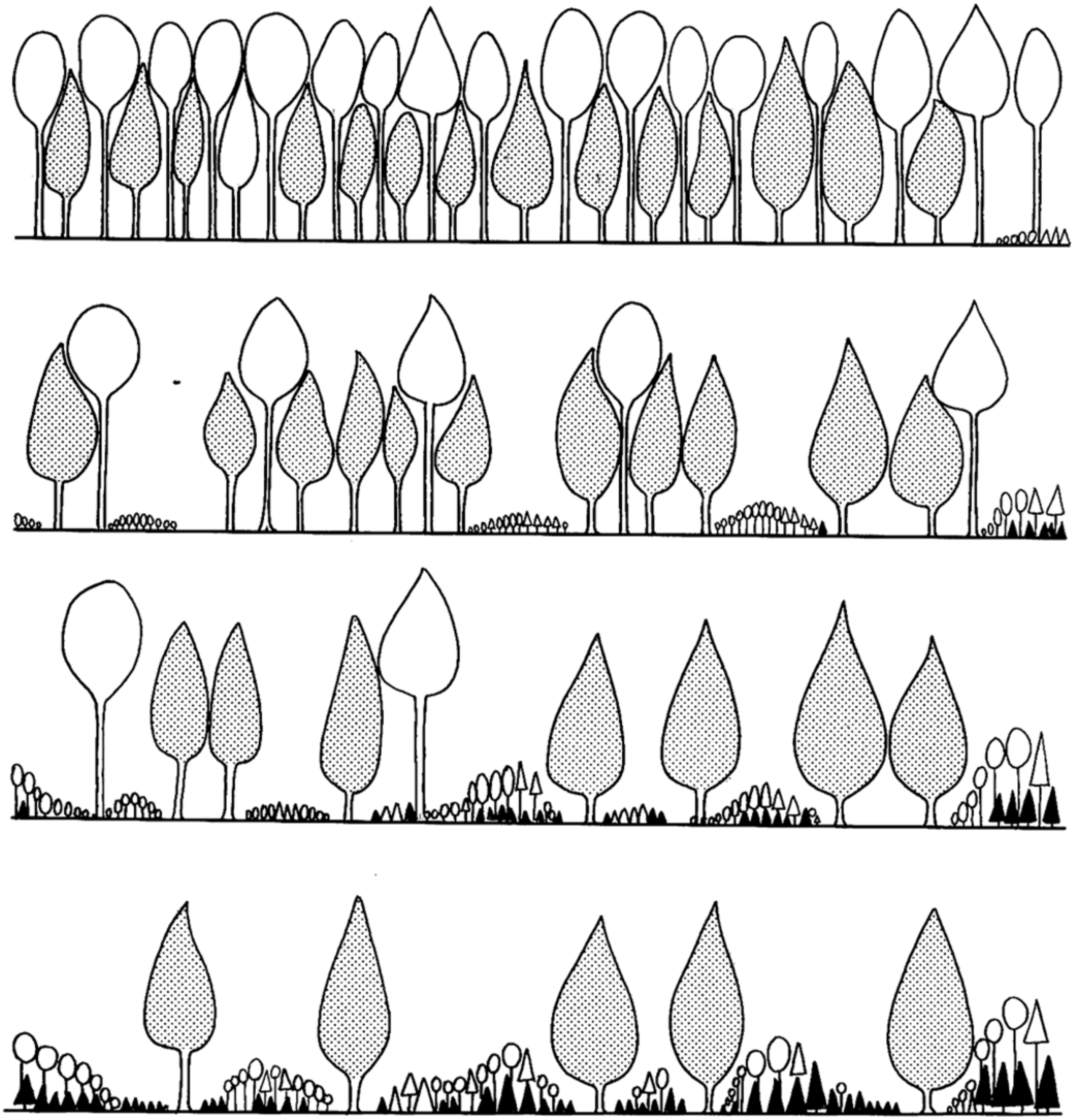


Figure 11.1 The general simplified pattern of structural development in a managed two-aged, mixed-species stand. An even-aged (single-aged) stratified mature stand in the top figure is harvested after two entries, progressively leaving scattered reserve trees of the shade-tolerant sub-canopy species in the center figure. In the bottom figure, the new age class has regenerated to form another mixed-species stratified cohort. It is important to leave enough reserves of the original forest behind for the structure and species composition that is desired, but they must not impede the growth of the new regenerating cohort. *Source:* Yale School of Forestry and Environmental Studies.

other terms have been used, including *green-tree retention* and *variable retention* in the western US and western Canada, and *deferment cutting*, *structural retention*, and *leave-tree method* in the eastern US. These names all arose in regions where clearcutting and planting was the standard regeneration method, and two-aged stands were being created as an alternative, primarily for habitat and aesthetic objectives. The most common terms used for methods focusing principally on conservation objectives are *variable retention* and *structural retention*. These terms are not used to describe a natural regeneration method but are used to describe the older age and size classes left in the stand after planting. As such they are treated under planting in Chapter 16.

Characteristics of Reserve Trees

When the objectives of creating a stand with two-aged structure focus on maintaining mature forest habitat and landscape aesthetics, a specific set of trees are often selected for reserves. These include (1) standing dead trees, (2) live trees with cavities and partial decay, (3) live trees with large crowns, (4) tree species that have particular crown morphologies that greatly enhance forest structure (i.e., evergreens within deciduous forest), (5) tree species that provide an important food source for many animals (keystone species), (6) late-successional tree species that take long times to mature and would be eradicated in normal-length rotations, (7) tree species that are uncommon in the stand, and (8) trees of important cultural or religious value. Perfectly healthy, straight, mature trees can be selected as well, but there is less concern for the windfirmness or vigor of at least some of these reserve trees, because they will continue to be useful for habitat structure when they are blown down or when they die and become snags.

When reserve trees are to be left for timber production, selection of these trees should follow the criteria generally used for thinning stands. The reserve trees must (1) be of the appropriate valuable species, (2) have good stem form, (3) be windfirm, and (4) have crowns of sufficient size to produce a stem-growth response to the larger growing space. Selecting a set of the largest valuable trees in the stand can meet these criteria, but it also leaves substantial timber value in the stand, exposed to the risks of decay or injury for an extended period. The decision is often made to retain trees in the upper canopy that have a smaller diameter but still meet the criteria for quality and vigor. These trees have low current value but high potential to increase in value, especially as they grow past the minimum diameter threshold for high-grade sawlogs and veneer. However, reserving old trees of intermediate or overtopped crown classes is generally a bad idea, because these trees will generally not be able to respond with increased growth after release (Table 11.1).

Table 11.1 A description of reserves used in irregular hybrid seed-tree shelterwoods in southern New England.

Species	Reserve function
Red oak	A hard mast food source for many species of game and rodents. Old wolf trees are important den structures for many mammals. Smaller trees are often left because of future timber value
White oak	A rich hard mast food source for many species of game and rodents. Old wolf trees are important den structures for many mammals
Shagbark hickory	The bark acts to shelter summer bats and serves as a hard mast source for many rodents and game
Sugar maple	Often a wolf tree of cultural value with expansive crown and large cavities. Smaller trees are often left because of future timber value and extending the successional age of the forest
Red maple	An important source of soft mast and a tree bole that is susceptible to cavities from its dieback and re-sprout growth habit
Basswood	A rare canopy shade-intolerant tree that is important as a source of honey
White ash	A source of food as a soft mast tree that is prone to dieback and cavities when large
Black cherry	An important summer–fall soft mast for frugivorous birds; a tree that has timber value
White pine	Emergent white pine crown structures provide nesting sites for many species of hawks, and thermal cover and seed source for year-round resident squirrels and birds
Hemlock	Arranged in groups or beneath a canopy seed-tree hemlock can provide thermal cover and vertical stratification from the canopy to the groundstory

Source: Mark S. Ashton.

Spatial Distribution and Numbers of Reserve Trees

There are two distinct spatial patterns of tree distribution that are used when planning the retention of reserve trees in a stand. These patterns can be categorized as **dispersed distribution** where individual trees are scattered across the stand area, and **aggregated distribution** where trees are retained in patches of intact groups of trees within the stand. These two types of retention can also be combined in the same stand. Most of the interest in using these methods is to reduce some of the negative effects of a timber harvest on a stand by maintaining an acceptable landscape appearance and maintaining some of the habitat structure for forest interior species.

With a dispersed distribution, **reserve trees** can be scattered in a uniform pattern across a stand or in a variable pattern, with some parts of the stand having no reserve trees (Fig 11.2). Some studies (British Columbia Ministry of Forests, 1997; Ribe, 2005) have shown that if about 25–40% of the original overstory trees are retained, a substantial number of people find the landscape acceptable, but 15% is not acceptable. However, dispersed trees at 15–40% density may provide nesting and foraging habitat for birds, but they do not help very much to moderate the open microclimate conditions of the stand (air temperature, soil temperature, and soil moisture), which are critical for many closed-forest species (Aubry, Halpern, and Peterson, 2009).

Figure 11.2 Group reserves of western larch after a clearcut. The reserves are purposely left for structure not as a source of seed. The site preparation involved burning and scarification of the stand. *Source:* Chris Schnepf, University of Idaho, Bugwood.Org. Reproduced with permission from Bugwood.org.

One of the problems with retaining dispersed reserve trees is that the number and distribution of reserve trees that provide an acceptable landscape appearance may be too dense to allow the young stand to develop. The general idea is that for the entire length of the planned rotation there should be no need for thinning the reserve trees to maintain growth of the young stand. However, there is little information on how a dispersed reserve overstory affects understory growth for an entire rotation. Most guidelines are based on modeling results or on studies of regeneration development for only the first one or two decades following harvest. However, there is some experience with the development of older two-aged stands that had been created by fire (Zenner, Acker, and Emmingham, 1998).

Studies of Douglas-fir in the Pacific Northwest show that the growth of regeneration would be reduced by 20% with an overstory basal area of only 15–20 ft^2/ac (3–5 m^2/ha) or 2–10 trees/ac (5–25 trees/ha) (Birch and Johnson, 1992; Hansen *et al.*, 1995; Acker, Zenner, and Emmingham, 1998). Somewhat greater percent growth reduction occurred in Appalachian hardwoods, with 22 ft^2/ac (5 m^2/ha) basal area, or about 15 trees/ac (36 trees/ha) (Miller, Korchenderfer, and Fekedulegn, 2006). With highly shade-intolerant species, such as longleaf pine, even this level may be too great to allow the continued height growth of regeneration; understory growth decreased by 40% under a basal area overstory of 22 ft^2/ac (5 m^2/ha) basal area (Palik *et al.*, 1997). Thus, it appears that it is necessary to lose growth of the younger stand if trying to meet landscape appearance. Leaving only a few overstory trees to allow regeneration to grow rapidly is acceptable, but may not meet other objectives, such as landscape appearance. More research in this area is clearly needed both on the growth impacts of reserves on regenerating stands and the value of reserves to different wildlife populations. A dispersed pattern is also the choice when reserve trees are being held in the stand for timber production. A uniformly dispersed overstory provides for a thinning effect among these reserve timber trees.

The **aggregated distribution** (also called **patch retention**, **patch reserves**, **group retention**, or **group reserves**) consists of retaining patches of a stand that are left undisturbed. These patches include trees, snags, shrubs, smaller vegetation, woody debris, and the intact forest floor. They are designed to provide refugia for a variety of plant, animal, and microbe species to survive the harvest disturbance, and then re-invade the new stand as it develops, thus speeding the recovery of those species within the new stand. Patches can be located at any place in the forest matrix, or around small wetlands, rock outcrops, uncommon plant species, or other features of ecological importance. Patches can be nearly circular in order to reduce edge effects and maintain mature-stand microclimatic conditions as much as possible in the patch center. Patches can also be in a tapered teardrop shape, oriented into the prevailing wind in order to decrease wind damage. Linear shapes can be useful as corridors for the movement of some animals, for visual screens, and for seeps, ephemeral streams, and permanent water bodies. These reserves can also help to retain snags. In some regions, worker-safety rules require that snags must be felled before any other tree cutting can occur within a specified distance of a snag. In these situations, undisturbed patches may be the only way to reserve snags.

With patch or group reserves, it is more logical to specify a proportion of the stand area to be retained rather than a basal area or number of trees. Guidelines

and regulations have been developed for retention of patches for habitat structure in some areas. These include the minimum number of trees to retain per stand area, and the minimum number and size of patch reserves (Elliot 1988, FEMAT 1993). In other cases, methods have been created to meet ecological objectives that go beyond minimum regulatory rules. For Douglas-fir stands in British Columbia, Mitchell and Beese (2002) set the goal of having 50% of a harvest area either within a group reserve or in the zone of influence of mature trees. The zone of influence is defined as being the area that is less than one tree height away from a mature tree, in which effects of the mature trees on microsite conditions, seed rain, and animal use are likely to exist. This goal can be accomplished with about 10% of the stand in group reserves with each reserve being approximately 0.6 acres (0.25 ha) in area. The groups and the zone of influence around the groups make up 63% of the stand area, with the remaining 37% in open conditions.

Application of Two- or Three-Aged Systems

Unbalanced multi-aged stands are a dominant component of mixed forests worldwide. Driven by one dominant cohort whose origin is from the most recent stand-initiating disturbance, these stands also reflect structures, species, and age classes from prior legacy disturbances. Depending upon the forest type and species or regeneration guild of focus, these forests can usually be regenerated by irregular seed-tree or shelterwood systems. The use of irregular systems is growing primarily because foresters now face the task of integrating many codominating social goals (e.g., wildlife habitat, aesthetics, timber) into natural forest stands. Irregular systems and their applications to North American forests have been reviewed by Raymond *et al.* (2009).

Although irregular systems have been promoted to provide a more balanced approach toward attaining multiple goals, there remain many unanswered questions. The concepts of using forest structures as key attributes for wildlife habitat have largely been assumed, but not rigorously tested. Recognition of “keystone” and “umbrella” reserve tree species for maintaining wildlife habitat requires well-designed experiments for testing (see review by Simberloff, 1999). In addition, the effects on the growth and dynamics of reserves on particularly shade-intolerant younger cohorts growing beneath, remains largely unquantified. More concrete guidelines still need to be developed. Examples of regional applications of irregular seed-tree and shelterwood systems are presented for a variety of forest types: coastal Douglas-fir of the Pacific Northwest; the mixed conifer forests of the Sierra Nevada; interior mixed stratified coniferous forest of the northern Rockies; southern pine forests; oak–hardwood forests of the east and south; Acadian spruce–fir–northern hardwood forest of northeast America; traditional uses in Central Europe; mixed dipterocarp forests of tropical Asia.

Coastal Douglas-Fir in the Pacific Northwest

Many of the forests in the Pacific Northwest are dominated by the highly valuable species Douglas-fir, western hemlock, and western redcedar. Management practices in this region have evolved over the period of 1880–1980, from selection cutting, to clearcutting with natural regeneration, to clearcutting with planting. The harvesting that prevailed from the 1960s through to the 1980s produced a dramatic change in forest structure and habitat; old-growth stands were being converted to Douglas-fir plantations, which were to be managed on a 60-year rotation. The cutting levels on a landscape scale were quite high so that a marked change in landscape structure was occurring in some areas. Controversies arose over appropriate management of public lands in Washington, Oregon, and northern California. The focus of these controversies was an endangered species – the northern spotted owl. The owl’s habitat is closely associated with large trees for nesting and closed-canopy stands for protection from raptors that prey on the young. These concerns expanded to studies of species of all taxa that are found only or mostly in old-growth forests (Ruggiero, *et al.*, 1991; Marcot and Thomas, 1997). Federal land management research and planning led to a set of guidelines for managing these forests. In addition to establishing large unmanaged reserve areas, there was a requirement for maintaining old-forest structures (“biological legacies”) within the managed forests. This led to the concepts of retention of various amounts of trees, snags, woody debris, and small patch reserves of intact forest structure (Franklin *et al.*, 1997). These ideas have been incorporated into silvicultural ideas and methods.

Guidelines for management of federal lands in the Pacific Northwest have been developed, based originally on maintaining habitat for the spotted owl. A combination of dispersed and aggregated reserve trees are used in true clearcuts on more sheltered northern aspects, and in seed-tree systems on more exposed and hotter sites to meet these and other ecological objectives. Current standards require the retention of trees on at least 15% of the stand area. Of that area, 70% must be in patch reserves with individual patches of 0.5–2.5 acres (0.2–1.0 ha). The other 30% can be dispersed reserve trees or patches smaller than 0.5 acre (0.2 ha). Reserve trees should be selected from the oldest and largest trees, and the patch reserves are to be permanent.

Much of the development of irregular systems using reserve trees for ecological conservation across North America and elsewhere has been a result of the controversies and responses in the Pacific Northwest.

Sierra Nevada Mixed Conifer Forests

The conifer forests of the Sierra Nevada are some of the most complex mixtures in the American west. The diversity of trees can be as many as 10 species with four predominant species: sugar pine, ponderosa pine, incense-cedar, and white fir. More than 50 years of fire suppression have led to an explosive recruitment of shade-tolerant white fir and an absence of shade-intolerant pine recruitment. This is particularly apparent for sugar pine, which has also been effected by the introduced white pine blister rust (Ansley and Battles, 1998; van Mantgem *et al.*, 2004). There is a current strong mandate to restore the structure and age-class distribution to one that is more resilient to fire and climate change, and on creating or retaining habitat for rare and endangered species such as the California spotted owl (North, 2012). The use of irregular shelterwoods that focus on the sugar pine and ponderosa pine to establish regeneration is one way of meeting these mandates. Studies show that creating large enough canopy openings of 1.2–2.5 acre (0.5–1 ha) is the most inclusive environment for all of the major mixed conifers with incense-cedar and Douglas-fir growing faster than ponderosa pine, and white fir and sugar pine growing the slowest. Small openings of 0.25 acre (0.1 ha) just promoted white fir (York, Battles, and Heald, 2003). However, opening size is not the sole guide for successful regeneration establishment. The importance of site treatments must also be recognized as a tool to re-introduce fire back into the landscape, particularly at the time of regeneration cutting (see Fig. 11.3). Proposed solutions need to be site specific, with fire and mechanical slash-removal treatments that vary across the landscape (Stephens and Moghaddas, 2005). The most effective treatments that reduced fuel loading and laddering were those that re-introduced prescribed burning.

Northern Rocky Mountain Mixed Conifer Forests

Some of the most complex mixtures of the northern interior-west are two- or three-aged stands. These develop naturally in some forest types of Montana, Idaho, and British Columbia, where stand-replacing fires occur at relatively long time intervals of about 80–400 years, depending upon site (Arno and Fiedler, 2005). Mixtures dominate the more sheltered mid to lower slopes as mostly even-aged stands, but their relative proportions change between fire-sensitive and fire-tolerant species, as do fire-return intervals that are defined by drier or wetter slope positions and aspect exposure. The fire-sensitive species include late-successional western hemlock and western redcedar restricted to sheltered slopes

(a) (b)

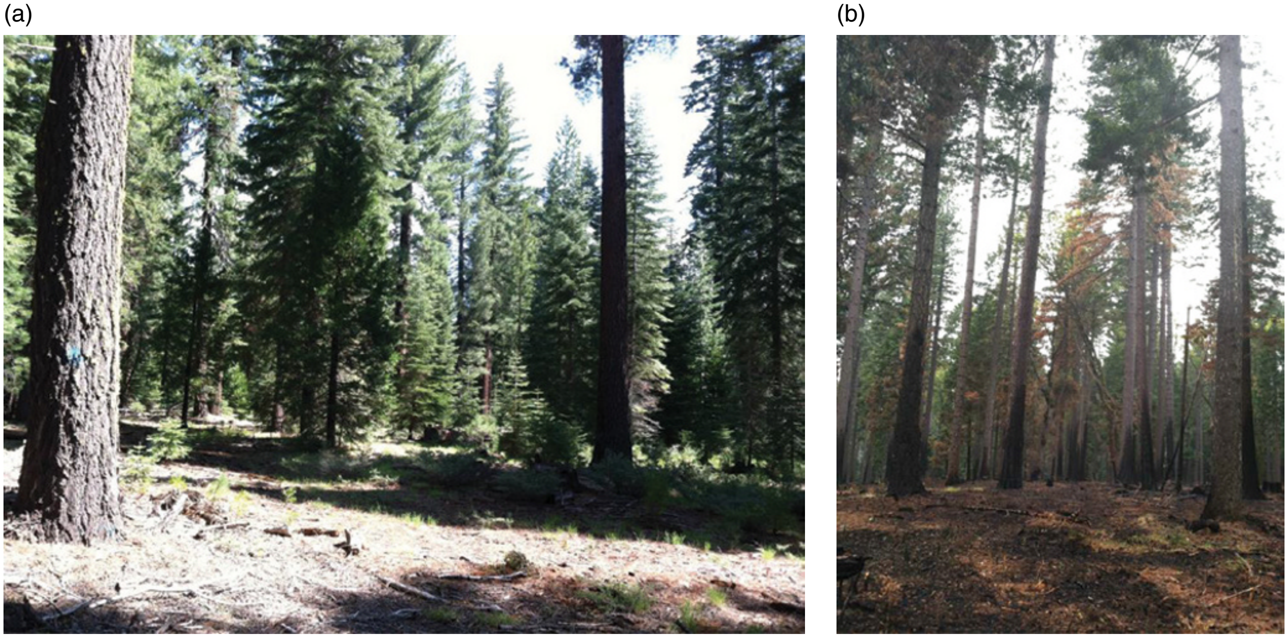


Figure 11.3 **(a)** The establishment cutting of an irregular shelterwood in the Sierra mixed conifer type comprising a 120-year-old pine–cedar canopy, fir of variable age mostly 40–60 years old, and a regenerating age class. Group reserves of white fir have been left with a spaced canopy of incense-cedar, ponderosa pine, and sugar pine. Slash was chipped and moved off site. **(b)** A prescribed burn followed the establishment cutting to expose the mineral soil in the same Sierra mixed conifer stand. The removal cut will take out about half of the spaced canopy and some fir where it is considered impeding regeneration release. *Source:* **(a, b)** Mark S. Ashton.

with moist soils, mid-successional western white pine, and early-successional white birch and black cottonwood. Western larch, lodgepole pine, and Douglas-fir are mid- to late-successional species that are considered tolerant of fire and predominate on southern exposures and drier sites (Arno and Fiedler, 2005).

On hotter, drier sites, as these mixtures approach 70 years of age from fire origin, the probability of a major fire increases because of the accumulation of fuels. A wildfire generally kills all of the lodgepole pine, but some of the Douglas-fir and western larch of the same age can survive, because of the protection provided by the thicker bark of these two species. The few older Douglas-fir and larch that had survived previous fires will also survive. After the fire, the pine seedlings regenerate from seed released from serotinous cones, along with wind-dispersed birch and willow. Douglas-fir and western larch originate from seed from surviving trees. The young mixed-species stand then grows up around the surviving trees. On more sheltered and moister sites and riparian areas, fire-return intervals can be up to 300–400 years. Western redcedar and western hemlock represent the late-successional dominants, and survive as advance regeneration or as legacy trees and patches where the fire did not burn because of the moisture. The regeneration assemblage is the same, except for the addition of seed from nearby hemlock and redcedar and from survival of their advance regeneration.

Silvicultural practices in this forest type for some drier-site stands mimic the natural pattern of disturbance by the use of seed tree with reserves (Fig. 11.4a). The older larch and Douglas-fir are retained as both seed trees and reserves; these trees are fire-scarred and have little timber value, but they produce seed and provide habitat structure. Some younger trees of these species are also retained as reserves, and the rest of the stand is harvested. This leaves the majority of the stand (lodgepole pine) unable to disperse seed. Mechanical site preparation is used in order to expose mineral soil and to push the slash close to the ground. The high temperatures from direct sunlight on the forest floor produce enough heat to cause the serotinous cones to open and release their seed. On moister sites, shelterwoods with single-tree reserves and patches or groups of reserves can be created, particularly using riparian zones to shape the patterns of reserves to be left. The remaining trees are the legacy old-growth western hemlock and western redcedar along the riparian zone as group or patches of reserves with single-tree reserves of Douglas-fir. Site treatments are not so severe and need to protect advance regeneration of fir, hemlock, and redcedar (Coates and Burton, 1997; Coates, 2002). Lodgepole pine and western larch are noticeably absent on these kinds of sites (Fig. 11.4b).

(a) (b)

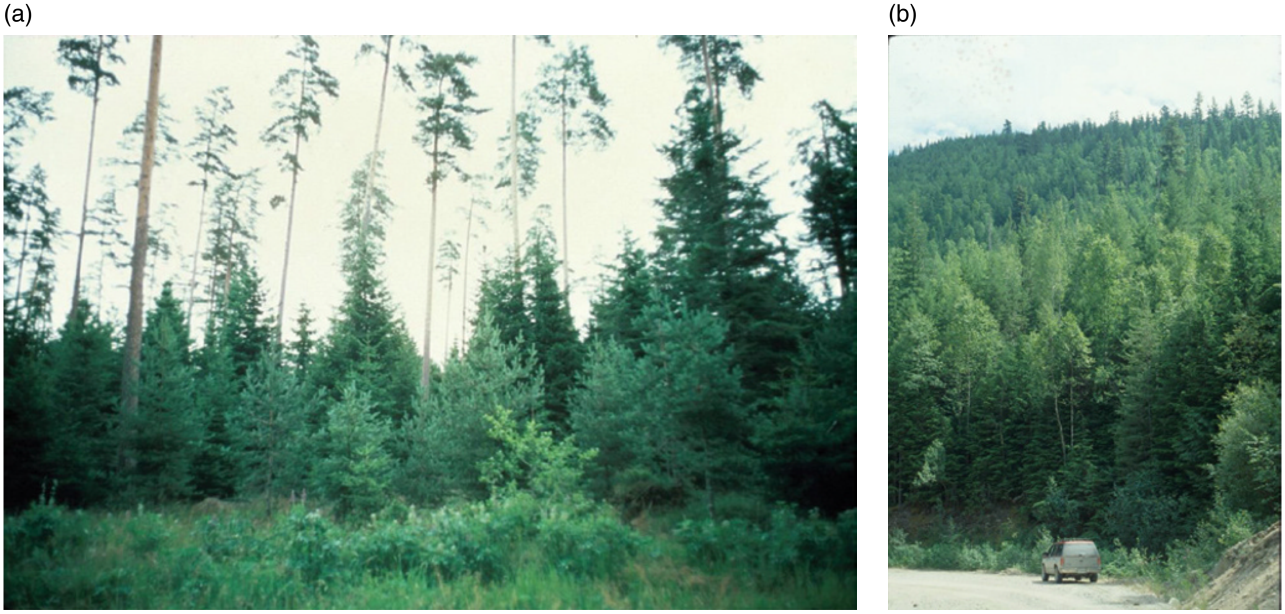


Figure 11.4 **(a)** A two-aged stand of Scots pine and Norway spruce with the younger cohort of pine and some spruce originating after a seed-tree cut. Sub-canopy spruce was left as reserves along with most of the seed-tree pines after the removal cutting 10 years ago. **(b)** A stratified three-aged interior cedar–hemlock stand in the Adams Lake region of British Columbia. The majority of the stand originated 40 years ago after an irregular seed-tree cutting with site treatments to reduce the fire risk (pile and burning). The 40-year-old mixture includes a canopy of birch and aspen, a sub-canopy of Douglas-fir and western white pine, and an understory of western hemlock and western redcedar. Reserves include 100- and 250-year-old Douglas-fir, western hemlock, and western redcedar, with survivors from the cut and prior mixed-severity fires. *Source:* **(a, b)** Mark S. Ashton.

Southern Pine Forests

When the land was settled in the southeastern US, longleaf pine forests predominated over large areas. In parts of their range, they formed unique open stands with a very diverse understory of wire grass and herbs that were maintained by frequent non-lethal creeping groundstory fires of lightning or human origin (Van Lear *et al*., 2005). These fires would have acted over a complex topography of dry ridge and ephemeral waterways, to create a patchy arrangement of oak–pine thickets in lower-lying areas to more open grasslands on dry uplands (Brockway *et al*., 2005). The longleaf pine was quickly exploited for its high-quality timber, and for pitch, tar, and turpentine for "naval stores" to waterproof the wooden boats for both the British and the American navies and their merchant fleets. Much of the land after exploitation was converted to agriculture or to loblolly pine plantations. Shortleaf pine and loblolly pine, as well as many oak species, co-exist with longleaf pine, but in the absence of frequent fires, the other species will take over and exclude longleaf pine. Fire control since the 1960s has not helped the incipient replacement by fire-tolerant longleaf pine of other tree species. Only 0.01% of old-growth longleaf pine remains, and the tree species itself is restricted to about 1% of its original range of 92 million acres (37 million ha), stretching from eastern Texas to southwest Virginia (Oswalt *et al*., 2012) (Fig. 11.5).

Several organizations and partnerships are involved in its restoration and conservation as an endangered ecosystem. The use of irregular shelterwoods has been promoted as one regeneration method that is appropriate to this system (Palik *et al*., 2003). Single-aged longleaf pine forests can be opened up with preparatory cuttings of a shelterwood that removes the sub-canopy. Light groundstory fires can be re-introduced, and an establishment cut could be made, with overstory retention of basal area of 30–70 ft^2/acre (6.9–15.7 m^2/ha) reserve trees, arranged as scattered individuals and in clumps to more closely resemble the complex structure of the original open forest (Palik *et al*., 2003; Van Lear *et al*., 2005). The open areas encourage establishment of natural regeneration, while the overstory reserves tend to reduce their survival and growth. Surface fires also tend to die out in these patches, allowing seedlings time to survive and grow beyond the grass stage. Over time, this makes for a more patchy series of multiple cohorts. It is important that no site preparation involving scarification should be done because much of the groundstory diversity could be destroyed (Van Lear *et al*., 2005).

Irregular seed-tree systems can be used for some of the other southern pine species, in particular for loblolly and shortleaf in situations where the conservation of retained trees maintains important wildlife habitat, especially for birds like the red-cockaded woodpecker. For loblolly pine, Gresham (1996) recommended overstory retention of 10 trees/acre (25/ha) with soil scarification, and prescribed burning or herbicide use to regenerate and establish a midstory of about 100 trees/acre (250/ha). However, retaining dispersed reserves of 10–40 ft^2/acre (2.3–9.2 m^2/ha) was directly correlated with the partial suppression of regeneration release from shading, rather than belowground root competition (Messina and Jenkins, 2000). For restoring the shortleaf pine–bluestem ecosystems in the Ouachita Mountains, a seed tree with dispersed single-tree reserves needs to achieve a standing

Figure 11.5 An irregular shelterwood (two- to three-aged) for longleaf pine with scattered and aggregated reserves. Site treatments included a prescribed fire prior to the establishment cut and again prior to the removal cutting. The youngest cohort has passed the grass stage and is about 2 years of age after release from the last prescribed burn. *Source:* Mark S. Ashton.

basal area of about 60 ft^2/acre (13.8 m^2/ha), felling most of the underbrush, followed by prescribed burning at 3–4-year intervals over the 10-year period since the cut (Hedrick *et al*., 2007).

Oak–Hardwoods of Eastern North America

The mixed hardwood stands of the central Appalachian Mountains and the Piedmont have a high tree-species diversity, with oaks, hickories, maples, yellow-poplar, beech, and black cherry as major components. In this region, seedlings became established from seedfall, from stump sprouts, or from the advance regeneration that is often present even in unmanaged mature stands. The uniform shelterwood is the normal protocol to be used to help establish advance regeneration, but if it is already present, then one-cut shelterwoods (overstory removals) are usually successful, and became the standard method for regenerating these stands for purposes of commercial forestry. However, in the 1980s, public dissatisfaction with the appearance of this kind of cutting led to the adoption of irregular shelterwoods on an experimental basis. Although improved landscape appearance was the initial objective, provision was made within the system for production of large-diameter sawtimber, continued production of hard mast for wildlife, and structural diversity for bird habitat.

Stands dominated by red oak and yellow-poplar on mesic sites of the central Appalachians were used to study the effects of reserves in shelterwoods. The 80-year-old stand had 160 trees/acre (400 trees/ha) before cutting, and there were 15 trees/acre (36 trees/ha) left as dispersed trees, giving 19% crown cover and 21 ft^2/acre (5 m^2/ha) basal area (Miller, Korchenderfer, and Fekedulegn, 2006). These were selected from the most vigorous codominant oaks in order to minimize epicormic sprouting or thinning shock. Some cavity trees, snags, and less common conifer species were also included as part of the reserves. Twenty years after the cut, the crown cover was 28%, and the basal area of the young age class was 35% less than in a similar stand with no reserve trees. The codominant stems of the regeneration had reached about one-half of the height of the 90 ft (30 m) tall reserve trees, and they will take 30–40 years to reach the height of the overstory. However, the reserve tree crown cover will likely reach 50% long before the younger age class reaches canopy height. From this experiment, alternative management strategies are being developed: (1) retain fewer reserve trees; (2) select species with restricted horizontal crown growth; (3) aggregate the reserve trees in clumps rather than dispersing them across the entire stand (Box 11.1).

In the drier oak–hardwood forests of Kentucky, studies by Lhotka and Stringer (2013) suggested that an irregular

Box 11.1 Regenerating oak–hardwood across till soil gradients in southern New England, using irregular seed-tree–shelterwood hybrids.

Introduction

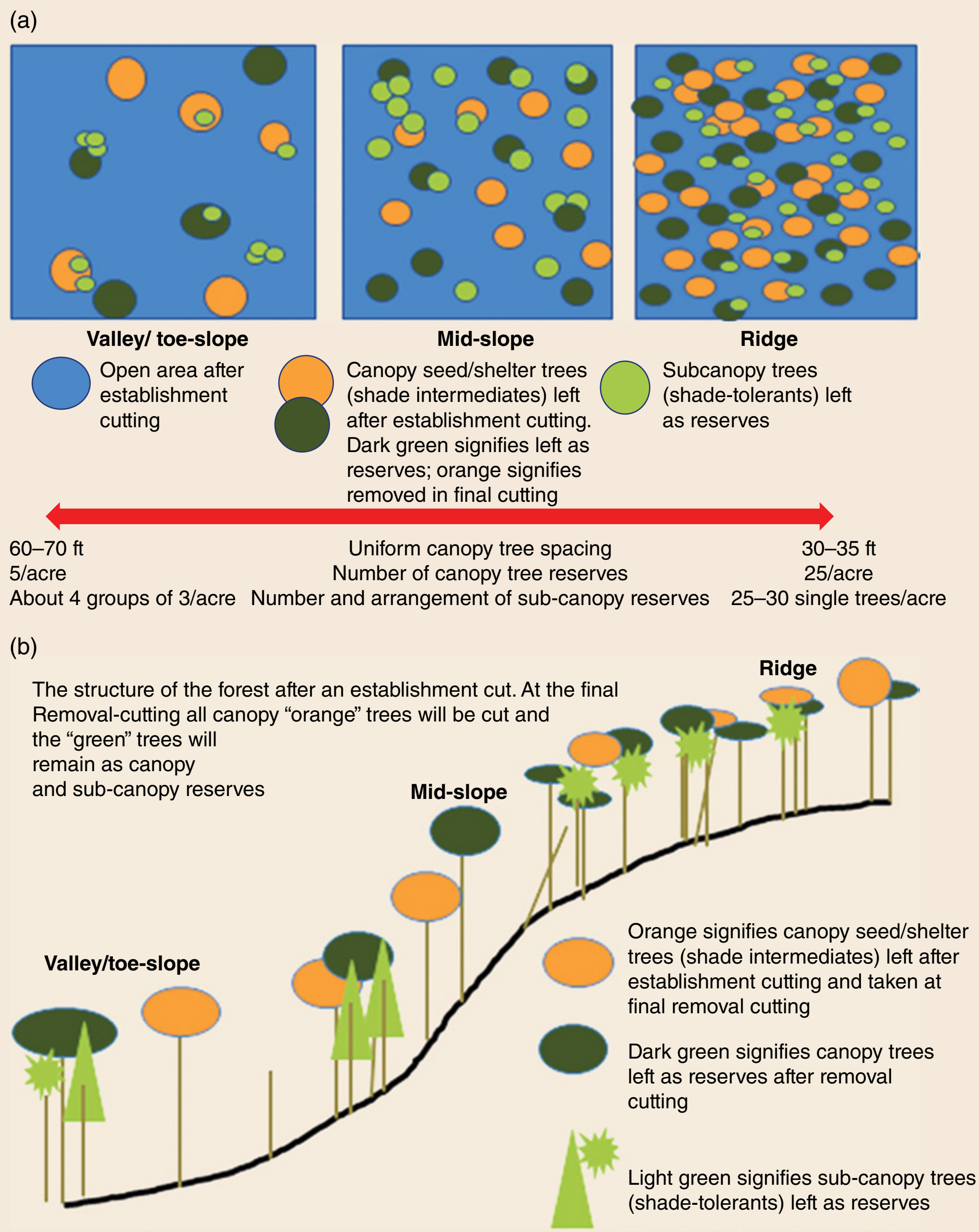
In southern New England, oak–hickory forest now dominates the canopy of second-growth hardwood forests that originated primarily beneath old-field white pine that was cut over for the packaging industry in the early 1900s. Most of this land was sheep pasture of varying quality belonging to subsistence farmers. In the 1850s, the land first grew back to old-field pine when people stopped pasturing livestock, because better land was available further west and employment became available in the new industries of the northeast mill towns. All the soils are glacial till soils that vary in depth, fertility, and soil moisture availability in relation to topographic position. Till soils on ridges are skeletal and droughty, while soils at the base of the slopes are mesic, deep, and fertile. The floristics of the second-growth hardwoods change in relation to slope position. In the lower-lying areas, canopy trees of red oak, ash, yellow-poplar, and shagbark hickory dominate with sub-canopies of sugar maple and understory trees of hop-hornbeam, musclewood, dogwood, and sassafras that also include an ephemeral herbaceous groundstory. On the ridge, red and black oak, white oak, and pignut hickory trees occupy the canopy with red maple in sub-canopy with a sedge–lowbush blueberry groundcover. To maintain the diversity of tree species into the future, but to also create greater resiliency to unforeseen pests, diseases, and disturbance, it is important diversify age-class and forest structure.

Regeneration

Studies have shown that successful recruitment of the canopy trees that are mostly all intermediate intolerants to shade (see Fig. 5.6) requires considerably more light in the understory to establish advance regeneration. In addition, these canopy tree species mast at very irregular time intervals and germinants are quickly extinguished within a few years because of the low light on the lower moister soils. On the ridge soils, regeneration can persist for many years building upon successive cohorts after each mast because of the brighter shade conditions. Approaches to regenerating this forest therefore changes in relation to slope position. Lower-lying deeper soils should be opportunistically cut during heavy mast years using the seed-tree method, where the spacing between trees is large, and reserves that are left for structural attributes or future timber value are grouped

(*Continued*)

Box 11.1 (Continued)



Box 11.1 Figure 1 (a, b) A graphic depiction of the changes in canopy-tree spacing and reserve arrangement and number for second-growth hardwood stands using the irregular seed-tree/shelterwood continuum across the valley–ridge landscape of southern New England. The crown size and structure of the canopy trees on toe-slopes are larger and the spacing further apart compared to those on ridge sites, where more smaller-crowned and shorter-statured canopy and sub-canopy trees can be retained at both establishment and removal cuttings. *Source:* **(a, b)** Mark S. Ashton.

together to minimize edge effect that mutes the establishment of the regenerating stand below (Fig. 1; Fig. 2a).

Stands on drier sites have advance regeneration prior to any regeneration cutting. The brighter shade conditions allow for an establishment cutting that can promote a closer spacing of the overstory and more sub-canopy reserves that can be arranged singly for greater structural heterogeneity (Fig. 1; Fig. 2c). For all sites, reserves can be chosen for many different habitat and timber values (see Table 11.1). Mid-slope sites have an approach to shelterwood cutting that is intermediate between ridge and valley (Fig. 2b).

Box 11.1 (Continued)

(a)

(b)

Box 11.1 Figure 2 **(a)** A seed-tree establishment cut on a mesic toe-slope. There are three age classes present: the regenerating age class (see photo inset of oak seedling sprout) including a mixture of regeneration from heavy-seeded tree species and pioneer tree species; the overstory mainly includes spaced 70 ft (20 m) oak, ash, and yellow-poplar, and group reserves of sub-canopy sugar maple and hemlock; the residual stand is even-aged (80 years) originating as second growth after old-field abandonment. There are scattered reserves of sugar maple wolf trees over 250 years old that were in the original pasture as shade trees. Site treatments included crushing slash and some intentional scarification with logging machinery. The harvest was done in the winter and photograph taken in the late spring (June). Inset: Advance regeneration of oak was small, sparse, and about 20 years old. Other advance regeneration included some shagbark hickory and more numerous sugar maple. Ash, yellow- poplar, paper birch, and the black birch and red maple coppice originated the growing season after the cut. **(b)** A mid-slope shelterwood establishment cut. There are about three age classes in the stand. The regenerating age class includes a mixture of advance regeneration and pioneer species. The overstory is mainly red oak spaced about 50 ft (15 m) apart, with single-tree and group reserves of sub-canopy hemlock, sugar maple, white oak, and red maple. The majority of the residual stand is about 90-year-old trees, originating as second growth on an abandoned brush meadow used as a summer sheep pasture. There are scattered reserves of white and black oak wolf trees over 300 years old that were kept in the original meadow to provide shade for livestock. Patches of advance-regeneration hemlock and white pine have been protected from a site treatment that crushed the laurel and slash to the ground. The removal cut will take about one-half of the canopy trees and the rest will be left as reserve structure.

(*Continued*)

Box 11.1 (Continued)

(c)

Box 11.1 Figure 2 (Continued) **(c)** The establishment cut of a shelterwood on a ridge site. There are three age classes present. The regenerating age class is comprised mostly of 2 ft (0.6 m) tall oak and hickory advance regeneration. Few pioneer species are represented in this age class because of the partial shade and droughty soil conditions. The overstory oak and hickory is spaced at 30 ft (9 m) with single-tree and group reserves of sub-canopy red maple, pignut hickory, and white pine. The stand is about 100 years old, originating beneath old-field white pine that was cut at the turn of last century (1900s). The removal cut will take about half of the canopy trees and the rest will be left as reserve structure. *Source:* **(a–c)** Mark S. Ashton.

edge effect can be used to build oak advanced regeneration. They suggest that the central oak–pine–hardwood region (Missouri, Kentucky, Indiana, and Illinois) can be managed with greater edge because of lower competition with shade-intolerant species. Lhotka *et al.* (2013) have proposed an irregular group shelterwood that retains continuous cover over the rotation, but follows the gap-based protocol of the group shelterwood. The difference is that the entries are punctuated across the period of rotation rather than being concentrated at the beginning, thus creating three or sometimes four age classes. This follows the work of Seymour (2005) in the more shade-tolerant Acadian spruce–fir forests of the northeast. Lhotka *et al.* (2013) propose group openings to be about twice the height of the surrounding canopy, with the sub-canopy removed in the surrounding forest matrix. If regeneration in the openings is not present, some soil scarification or vegetative competition control may be needed, supplemented by enrichment planting. Shade-intolerant species like yellow-poplar and shortleaf pine can colonize the centers of the openings, while oak will establish on the outside and inside edges. Periodic but infrequent entries into the stand to create new openings can also be used to expand existing openings to release the developing oak reproduction resulting in a diverse mixed-species stand. Whether this is balanced or unbalanced in age class, it is either an irregular group shelterwood (unbalanced) or group-selection system (balanced) (see Chapter 13). Work by Loewenstien (2005) on converting even-aged hardwood stands in Missouri to uneven-aged ones is very similar, but because of the more balanced approach to age-class distribution, it meets the description of the selection regeneration method, rather than an irregular shelterwood (see Chapter 13).

Acadian Spruce–Fir–Northern Hardwood Forest of Northeast America

The Acadian Forest includes the maritime provinces of Canada (Quebec, New Brunswick, and Nova Scotia) and northern New England (northern Maine, Vermont, and New Hampshire). The region is defined by its climate, where moist air from the Gulf Stream converges with the cold waters of the North Atlantic. This is reflected in the

convergence of the boreal spruce–fir (red spruce, balsam fir, paper birch, and aspen) with northern hardwood (beech, sugar maple, red maple, and yellow birch) (Loo and Ives, 2003).

Small-scale disturbance regimes (wind storms, insects, pathogens) to drive forest stand dynamics, have been documented before European colonization (Wein *et al*., 1987; Seymour, White, and Maynadier, 2002). Small-scale, patch-like disturbances were scattered and the disturbances peaked at periodic intervals, presumably correlated with supra-annual periodicity in droughts, floods, and windstorms. Studies suggest no large compositional changes, but primarily differences in age class and structure (Seymour, White, and Maynadier, 2002; Saunders and Wagner, 2008). The shade-tolerant spruce, eastern hemlock, beech, and sugar maple predominated, primarily because disturbance regimes provided their advance regeneration an advantage; all are able to endure suppression and respond to release, and all three species are long lived (Wein *et al*., 1987; Boucher and Grondin, 2012). Widespread fire has been documented to occur, but only at very long time intervals of approximately 800–3000 years. No evidence suggests that stand-replacing disturbances played a large role in the forest dynamic at smaller intervals of time (Fraver and White, 2005; Boucher and Grondin, 2012).

The Acadian forest post colonization has witnessed dramatic changes in composition and structure, primarily from a periodic series of ever more intense harvests for timber and pulpwood. The forest is dominated by early-successional species (red maple, balsam fir, paper birch, aspen) and beech coppice growth from the recurring effects of the introduced beech-bark disease (Seymour, 1992; Loo and Ives, 2003). In the distant past (1880–1940), the logging could mostly be defined as a diameter-limit cut, which had no silvicultural rationale other than to extract dimensional wood for sawtimber. Post World War II, the advent of the pulp markets promoted the present-day landscape, which is fragmented and dominated by block-shaped one-cut shelterwoods (also called "commercial clearcuts") (Fig. 11.6). Reliance is almost entirely upon release of advance-growth balsam fir and sprout growth of hardwoods. Some commercial companies rely upon creating conditions of true clearcuts by scarification and use of herbicides, but only for planting purposes for spruce and fir.

Recent research has demonstrated that those forest areas deemed to be managed in a less intensive way can be regenerated using a variety of partial cutting techniques, some of which would be defined as irregular shelterwoods (Seymour 1992, 2005; Saunders and Wagner, 2008; Brais *et al*., 2013; Bédard *et al*., 2014; Lussier and Meek, 2014) (Fig. 11.7). Such systems can vary dramatically by site and species. The most sophisticated least intensive harvest systems are designed to create disturbances that would not exceed 1%/year (Seymour and Kenefic, 1998; Arsenault *et al*., 2011). These can be considered selection systems, and are treated elsewhere (see Chapter 13). The more intensive partial harvests that can be considered an irregular shelterwood would remove about 50% of the standing basal area. This was done by harvesting mature trees in patches where advanced regeneration was present, or scarifying areas in harvested patches where advance regeneration was not present (Lusier and Meek, 2014). Seymour (2005) argues for a more sophisticated hybrid approach between shelterwood and selection that he calls an irregular group shelterwood with permanent reserves of late-successional trees. Over the course of the rotation, they more intensively create and then expand the groups over a series of entries for the first 50 years, and then leave them untreated for the remaining years. In this way, there is no balanced age-class approach, but the mandate of 1% per year over 100 years is not exceeded.

Traditional Uses in Central Europe

Two-aged silvicultural systems have been used for timber purposes in central Europe since at least the 1800s. This was primarily for the production of ship masts and more recently for veneer logs. Scots pine, European larch, sessile oak, and European beech were the species used for reserve trees (Troup, 1952; Burschel and Huss, 2004). These systems included seed tree with reserves, with pine and larch left as dispersed trees (Valkonen, 2008). The rotation age was 120 years for these stands, and all trees were harvested at that age except for 8–15 trees/acre (20–37 trees/ha). To produce satisfactory and timely regeneration, the stand was then replanted if no natural regeneration had established. When the younger age class reached the rotation age of 120, all of the 240-year-old reserve trees were cut, as well as most of the 120-year-old trees, leaving only a new set of reserves. The younger stands growing beneath the reserves were thinned, following usual practices. During thinning, some trees were designated as future reserves to be grown for two rotations, and these trees were given additional growing space during the thinning. Reserve trees would be kept to the end of the 240-year rotation, unless the trees could be felled with their crowns landing in a forest road, avoiding damage to the stand. In some applications of this method, only trees within one tree-height of a forest road would be selected as reserve trees, so that they could be felled in mid-rotation. The greatest problem with this two-aged system for timber production was windthrow of the reserves, losing the value of the large trees and damaging the young stand as well. Wind damage has been so frequent that this system has declined in use in recent decades (Matthews, 1989; Burschel and Huss, 2004). Another issue has been the

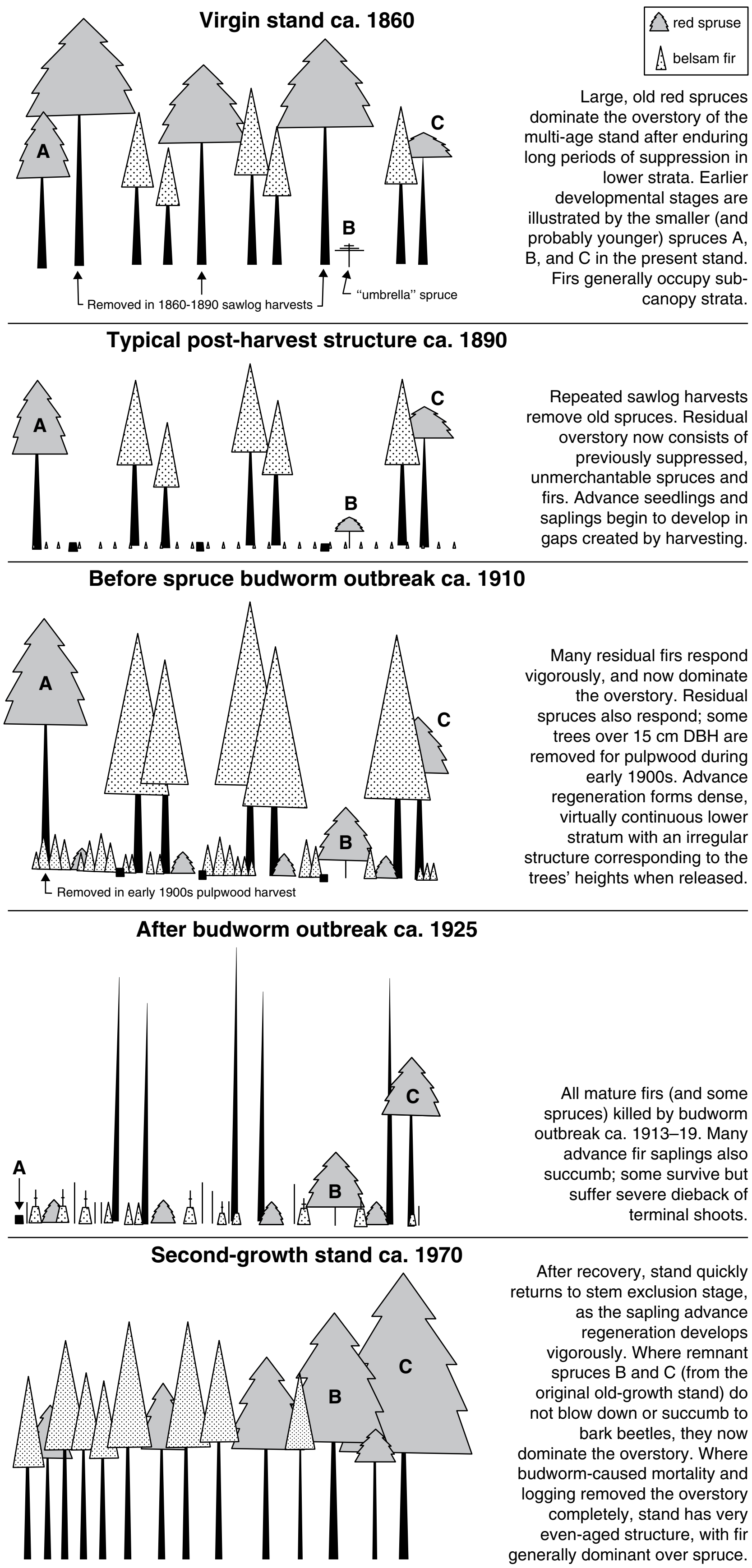


Figure 11.6 History of forest cutting in northern Maine. *Source:* Seymour, 1992. Reproduced with permission from Springer.

Figure 11.7 A stand in central Maine which has just been thinned, with removals from each of the strata and with sufficient opening of the lower-most stratum to allow establishment of new advance regeneration. The canopy includes oak and eastern white pine, and the sub-canopy is mostly hemlock, red maple, and beech. *Source:* US Forest Service.

reduced growth of the younger cohort from the shade of the reserves; this is particularly the case for shade-intolerant Scots pine (Valkonen, 2008). An alternative for producing these very large high-quality timber trees has been to set aside some entire even-aged stands for long rotations.

The use of reserves for high-quality timber production still continues in Europe. Shelterwood with reserves is used in Germany and France with mixed stands of sessile oak and European beech. About 10 trees/acre (25 trees/ha) of oak are retained as reserves at the final shelterwood removal cut. Timber value is lost when epicormic sprouts form on oaks when they are suddenly released in the final cut. To counteract this, beech is sometimes retained in the lower canopy just around the reserve oaks, in order to shade the oak stems and suppress any epicormic sprouts that develop (Burschel and Huss, 2004).

Mixed Dipterocarp Forests of Tropical Asia

The tropical forest types that are the most timber rich are mostly in southeast Asia. They are represented by one family of trees that dominates the canopy of these rainforests, the *Dipterocarpaceae*. This family comprises the timber-tree genera *Shorea*, *Dipterocarpus*, and *Dryobalanops*. Standing commercial timber volumes are far higher per acre (10,300–34,300 bdft/acre; 60–200 m^3/ha) than any other tropical forest type in Africa or Latin America that have valuable but sparse amounts of timber per acre (850–8500 bdft/acre; 5–50 m^3/ha).

Irregular shelterwood systems in Asia have a diverse and long history. Mixed dipterocarp forest types that are relatively shade intolerant (red *meranti* type) and that contain merchantable volumes of timber greater than 6850 bdft/acre (40 m^3/ha) are very suited to the classical uniform shelterwood, where preparatory treatments are focused at establishing advance regeneration of the shade-intolerant canopy trees prior to canopy removals (see Malaysian Uniform System in Chapter 10). However, where mixed dipterocarp forests have merchantable timber volumes below 10,300 and above 4300 bdft/acre (below 60 and above 25 m^3/ha), irregular shelterwoods are more appropriate (Ashton and Hall, 2011). Irregular shelterwoods are appropriate for slower-growing, more shade-tolerant, mixed dipterocarp forests of the uplands.

Simple systems were developed for the Asian mixed dipterocarp forests usually on more fertile soils (see Chapter 10 for uniform shelterwood systems). In the more floristically rich upland hill regions of tropical Asia, dipterocarp forest types are often poorly stocked with advance regeneration. More complicated shelterwood treatments that follow the classical methods to secure advance regeneration are used, but that leave much of the overstory structure behind after final removal cuttings

such that the stand is managed as an unbalanced two to three age-class system with one dominating successional age class. In all cases, because of sparse amounts of advance regeneration and/or more unpredictable masting shelterwood treatments, one must first ensure establishment of more advance regeneration through preparatory cuttings that remove the understory and sub-canopy before any canopy trees are removed. Once advance regeneration has been satisfactorily established, canopy trees can be left within new stands as an older overstory reserve age class. For example, in the Andaman Islands, the understory is gradually raised in a series of preparatory and establishment cuttings such that the regeneration grows to a pole-size class before the overstory is partially taken off (Chengappa, 1944). This means that at any one time, at least two age classes of trees are present within the stand and over many periods there are three. In the mixed dipterocarp forests of the Western Ghats mountains, the partial removal of the canopy and the complete removal of the understory and sub-canopy over about a decade, allow for the establishment and release of very shade-tolerant regeneration susceptible to dieback from over-exposure to direct sun (Kadambi 1954). Recent work in Sri Lanka, for a similar forest to that of the Western Ghats, has developed shelterwood systems that differ in their aggressiveness and timing of canopy removals in relation to topographic position from valley to ridge (Box 11.2).

Box 11.2 Regenerating mixed dipterocarp rainforest across topographic gradients of upland hills in Sri Lanka.

Introduction

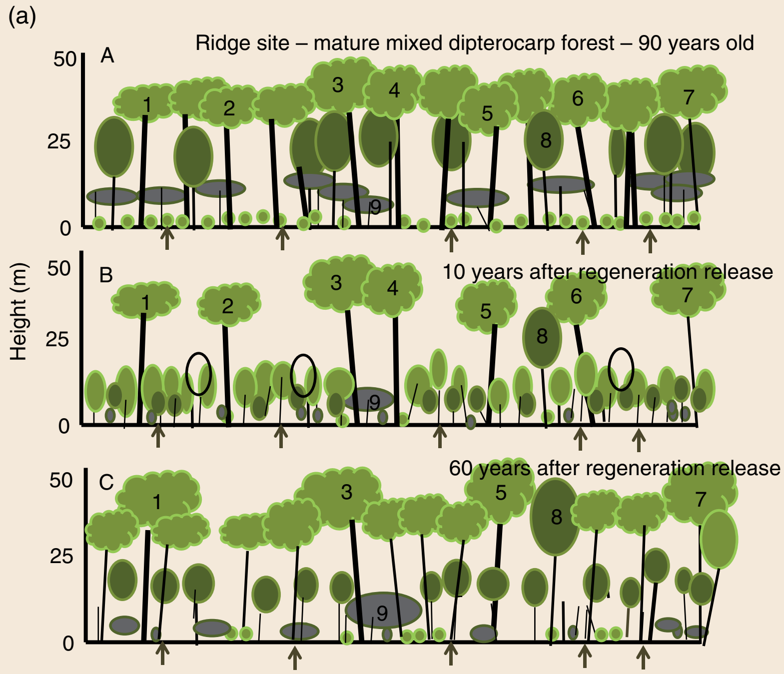
The hill mixed dipterocarp forest type itself is restricted to elevations between 650–3300 ft (200-1000 m) above mean sea level on undulating ridge–valley topography of metamorphic origin. Soils are very old weathered *in-situ* ultisols (Nachtergaele, 2001; Soil Survey Staff, 1999) in a climate that has greater diurnal variability (mean 18 °C/64 °F) and an ever-wet climate that has an annual rainfall between 3000–6000 mm (120–240 in). Studies suggests the same overall approach as for other mixed dipterocarp forests – the use of shelterwoods. However, they are site specific, with the amount of parent tree and residual overstory that are left after regeneration establishment, increasing to serve as an increased source of seed and shade on progressing upslope. Greatest retention is thus on the ridges which include the most shade-tolerant canopy tree species (*S. worthingtonii–M. nagassarium*).

Regeneration

On the ridges, such a system would resemble the work done in the Andaman Islands, India. The best silvicultural term to define this method would be a "cyclical irregular shelterwood." To initiate the process, the sub-canopy is cut for a preparatory treatment to increase understory light regimes and release growth of advance regeneration of the canopy tree species. Sprouting species of non-timber forest products (NTFPs) such as *Agrostistachys intramarginalis* need no other treatment other than periodic harvest of leaves as an NTFP. However, their growing space needs to be restricted because of competition with advance-regeneration establishment. Other species of NTFPs or timber tree species that are density dependent with widely scattered dispersal (e.g., ebony) need to be enrichment planted during this period. Continued control of the understory by cutting back sprout growth of the severed stems of the understory trees needs to be done. After a 10-year period, about half of the basal area of the canopy is removed, leaving the rest to close the canopy before another 50% canopy removal 30 years onward, to allow the original regeneration, now pole size class, to attain the canopy (Ashton and Peters, 1999). The process is repeated at year 60, and again at year 90 such that three cohorts (age classes) of canopy trees ascend through the strata at any one time (Figs. 1a, 2). Compared to the valley and mid-slope sites a relatively higher basal area and stem density can be carried within the prescriptions at all times.

On valley sites, the canopy tree association is much more shade intolerant and a more heavy-handed approach can be taken, that resembles a one-cut shelterwood (Ashton and Peters, 1999; Ashton 2003). Trees left behind are designed to not be removed until the next regeneration entry. Enrichment planting of NTFPs and cleaning and liberation release treatments (see Chapter 20) follow establishment of short-lived pioneers that quickly can form an umbrella canopy of shade over advance regeneration after a single-entry cutting that removes the overstory. It is important to monitor and to carry out judicious release work of advance regeneration and plantings for the first 10 years before leaving completely alone. No other major intrusions should be done until the start of the next rotation at about 50–60 years. It is a relatively simple system but the harvest of early (*Macaranga peltata*, *Alstonia scholaris*, *Coscinium fenestratum*, *Calamus zeylanica* at 10-20 years), and mid-seral (*Garcinia morella* at 25 years and onwards) NTFPs should be important economic

Box 11.2 (Continued)



Box 11.2 Figure 1 (a) Profile A depicts the stylized and simplified condition of a ridge site stand, prior to regeneration treatment with slow-growing late-successional *S. worthingtonii–M. nagassarium* trees in the canopy (represented by light green crowns), and their advance regeneration in the groundstory as saplings and seedlings as small circles of the same color. Sub-canopy tree species are represented by dark green vertical ovals and understory tree and shrub species by horizontal dark gray ovals. Profile B depicts the stand after the sub-canopy has been removed to release growth of advance regeneration. Control of sprout growth of the understory and sub-canopy species has been completed to insure the release of the shade-tolerant slow-growing canopy trees. Enough light has allowed some pioneers of stem exclusion to dominate in places as depicted by the open black circles. Profile C depicts the stand after at least one more entry, removing 50% of the canopy. Three age classes are now present of canopy dominant trees *S. worthingtonii* and *M. nagassarium* – the original canopy trees prior to start of treatments (illustrated by numbers 1, 3, 5, 7); their original regeneration that has now grown up as the 60-year-old canopy trees; and their advance regeneration waiting for the next partial canopy removal at year 90.

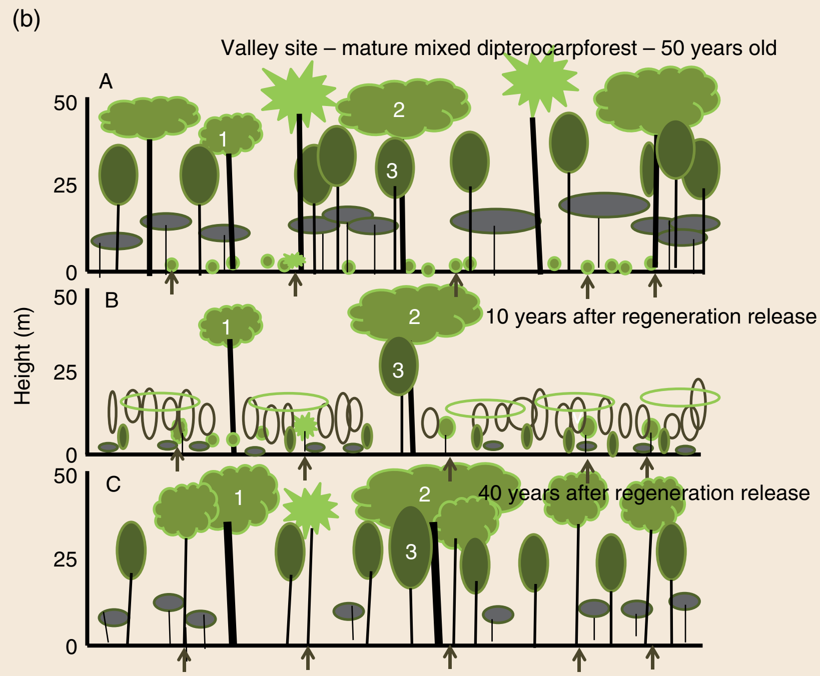
additions to the management of the stand for timber (Figs. 1b, 2).

Under shelterwood treatments on the mid-slope association, less than a quarter of the basal area remains after logging (<50 ft^2/acre; <12 m^2/ha) usually comprising overstory canopy reserves of *S. trapezifolia*. Basal area rapidly increases to 85 ft^2/acre and 650 stems >1 in (20 m^2/ha; 1600 stems/ha >2 cm DBH) after 10 years regrowth, and 108 ft^2/acre and 500 stems >1 in (25 m^2/ha; 1260 stems/ha >2 cm DBH) after 20 years (Ashton *et al*., 2011). During early stand re-growth mortality from self-thinning is 2% per year. Stocking on such sites is good with advance regeneration of canopy timber species normally occupying the groundstory (<3 ft; 1 m) in numbers ranging from 40,500–80,000 stems/acre (100,000–200,000 stems/ha). Seldom do seedlings of *S. trapezifolia* and *Syzygium rubicundum* species survive longer than 3 years unless released by the creation of a canopy opening. New cohorts supplement regeneration annually.

Supplemental enrichment plantings of *Diospyros quaesita* (ebony), *Caryota urens* (sugar palm), *Elletaria ensal* (cardamom) (Fig. 3a), and *Calamus zeylanica* (cane) can be done using containerized stock. *Diospyros quaesita* should be planted together in groups of three, since investigations have shown nearly 50% mortality after planting, and therefore group plantings are more desirable to ensure full enrichment stocking. At least two cleanings are required at 3 and 6 years after planting. Planting of *Caryota urens* at 82 ft (25 m) spacing is an alternative that could also supplement natural regeneration (Fig. 3c). The palm is susceptible to porcupine damage and a foliar fungus, both of which have been recorded to signifi-

(Continued)

Box 11.2 (Continued)



Box 11.2 Figure 1 (Continued) **(b)** Profile A depicts the stylized and simplified condition of a valley site stand, prior to regeneration treatment with *S. megistophylla* and *D. hispidus* trees in the canopy (represented by paler green puffy and star-shaped crowns). Sub-canopy trees are represented by dark green vertically oval shapes and understory trees and shrubs have dark gray horizontally spreading shapes. The numbered trees are those that remain after treatment to grow further. The arrows point to advance regeneration of the canopy that are released in future canopy-removal treatments. Profile B depicts the stand structure and composition 10 years after overstory removal with reserve trees (1, 2, 3) judiciously left behind because of ecological or economic value and can be removed only at the next regeneration entry in 50–60 years time. At 10 years the young stand is dominated in the canopy by pioneers of initiation (depicted by open horizontal green oval lines) and stem exclusion (depicted by open vertical ovals). The advance regeneration present before treatment has been released and grows more slowly beneath the pioneers. Profile C depicts an essentially even-aged, mixed stratified stand after 40 years of growth and development, with a few older reserves left after the original cutting. No major intrusions have been done other than to harvest the early-successional non-timber forest products. The pioneers have either been harvested or died from being over-topped by the current canopy of 40-year-old (plus) *S. megistophylla* and *D. hispidus* that was released originally as advance regeneration. Sub-canopy and understory trees of the same age but largely of vegetative origin, fill out the strata. Understory re-initiation of advance regeneration of the canopy tree has not yet started. *Source:* **(a, b)** Adapted from Ashton *et al*., 2011.

cantly affect survival. Cleanings around the planted palm need to be done once established. However, the palm can grow well in partial openings, and matures within 15 years providing an inflorescence for tapping once a year for the next 10 years. Flowers can be tapped on average for 30 days yielding 6.5 lb (3.0 kg) of sugar/day/tree. *Elettaria cardomomum* var. *major*, the native cardamom, can yield over 100 fruit/year 3 years after planting. However, the shrubs require yearly cleaning and an open environment providing periods of direct sun for best yields. This limits suitable planting sites to skid trails and landings (not more than 10% of the stand area in a well-planned timber harvest). Plants can only productively exist until canopy closure over skid trails. This occurs by year 8 in shelterwoods. For shelterwood systems, the productive cultivation period is estimated to be a 5-year period at the beginning of a 60-year rotation. *Calamus zeylanicus* (rattan, cane) is a climbing palm that can grow more than 3 ft (1 m) each year, reaching lengths of over 64 ft (20 m) 15 years after planting (Fig. 3b). Cane requires open conditions and a young regenerating forest stand for best growth. It survives well after planting but its reliance for support on young timber saplings can affect their form. Judicious spacing is important.

Box 11.2 (Continued)

Box 11.2 Figure 2 A photograph of the topographic gradient with ridge, mid-slope, and valley forest, treated to differing degrees of canopy removal by irregular shelterwoods. *Source:* Mark S. Ashton.

(a) (b)

Box 11.2 Figure 3 (a) Cardamom shrub enrichment planted in the forest understory. **(b)** Cane (*Calamus* spp.) emerging into the canopy during the stem-exclusion stage of stand development about 15 years after the establishment cutting.

(*Continued*)

Box 11.2 (Continued)

(c)

(d)

Box 11.2 Figure 3 (Continued) **(c)** Sugar palm (*Caryota urens*) being tapped for syrup that is boiled down into **(d)** cakes of brown sugar. *Source:* **(a–d)** Mark S. Ashton.

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12

Natural Regeneration: The Coppice Method

Introduction

Silviculture that depends on vegetative sprouting is not only remarkably simple and successful, but is also the most common and ancient kind of forest regeneration. With the right species and sizes of trees, the old forest crop is merely cut down and a new young forest dependably sprouts back. Its current use in the less-developed countries makes it the most widespread method of regeneration on more forest areas than any other form of silviculture (Panel on Firewood Crops, 1980, 1983; Sims *et al.*, 2006). Vegetative regeneration is so easy, at least where it is practical, that special measures are seldom necessary; in fact, it is difficult to prevent it where it is not wanted.

A **low forest** is forest that originates vegetatively from natural sprouts, or in some cases, layered branches. It is contrasted with a **high forest**, which develops from seeds or planted seedlings. The ancient Germanic origin of these terms refers to the fact that most sprout forests in Europe were grown on short rotations, and the trees therefore never grew very tall. The term **coppice** denotes a stand that grew from sprouts. In the **simple coppice method**, all standing trees are cut at the end of each rotation, and an even-aged stand springs up almost immediately. A special form of coppice management is **pollarding**, in which the tops of trees are removed, thus inducing them to sprout at points above the reach of browsing animals. The planting of rooted cuttings or other asexually regenerated material does not become a coppice stand. It is only after the initial stand has grown and been cut that the next stand becomes a coppice stand.

Vegetative Regeneration and the Nature of Disturbance

The ability of plants to reproduce vegetatively is of tremendous survival value for many species of perennial plants. It is the normal regeneration mode for most shrub species and grasses, many herbaceous forest plants that have perennial roots and annual shoots, and some species of trees. For example, the coast redwood, which is the tallest of all plants, commonly reproduces by sprouting (Fig. 12.1). For such species, sexual regeneration from seed may be a safety factor that persists and preserves capacity for genetic change and adaptation to new conditions. For many other species, mostly angiosperms, sprouting is just an additional mode of

Figure 12.1 A ring of very large stump sprouts of coast redwood surrounding the charred remains of a stump about 8 ft (2.4 m) in diameter near Santa Cruz, California. *Source:* Mark S. Ashton.

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

regeneration. For others, including many conifers, it never occurs or is infrequent.

Vegetative regeneration can be from **rhizomes**, which are modified stems that grow underground, often near the soil surface. Rhizomes are often associated with grasses. Their re-growth can be vigorous particularly after fire. Grasses produce both roots and shoots from the nodes of the rhizomes, and they store carbohydrates during the winter and then produce shoots and roots in the spring. Both sprouts from woody plants and rhizomes from grasses provide good browse and fodder for wild or domesticated animals. Vegetative regeneration is also the traditional mode of fuelwood production throughout much of the world. It is generally considered a poor means of timber production because the stems are often considered small and mis-shaped, but this opinion may be because of cases in which the technique has been used inappropriately.

Forest and woodland regions that are prone to repeated chronic disturbances like frequent recurring fires, droughts, floods, high winds, and avalanches, promote plants to almost exclusively reproduce vegetatively. The aboveground portion of the plant may die back or be damaged at the occurrence of a disturbance, but the root system or basal part of the stems remain intact and can resprout. Plants have evolved and adapted to survive such disturbances, probably from their continuous long-term exposure of thousands to even millions of years. Knowledge of areas and sites which are prone to repeated disturbance and that require restoration and soil stabilization, promotes the thoughtful planting of species that have prolific sprouting ability (e.g., riparian and watersheds, coastal dunes and beaches, and disturbance-prone hillsides). A species can thus maintain itself in the face of disturbances that occur so often that no individuals reach seed-bearing age.

Places where disturbances within forests occur between long time intervals (windstorms, tree falls in old-growth stands) or when a disturbance happens that is cataclysmic (i.e., very hot crown and ground fires, volcanic eruptions, huge landslides and mudflows) dependence on vegetative regeneration is low because the whole plant succumbs including the roots belowground.

Finally, vegetative reproduction predominates in environments and forest habitats where there is an absence of pollinators necessary for sexual reproduction. Forest understories associated with everwet, moist tropical, and temperate forests have many species that rely on vegetative reproduction (see Chapter 5). In these environments, light can be so limiting that sexual reproduction is an expensive luxury. Many of our most important traded beverages (tea, coffee, cocoa) were originally plants of the forest understory but now their chief mode of cultivation is by cuttings and coppice systems.

The Physiology and Morphology of Sprouting

A shoot that arises from a tree stump will grow much more rapidly than a new true tree seedling of an equal age and species. Much of this difference can be accounted for by the fact that the rapid growth of young coppice sprouts relies upon an extensive root system and carbohydrate supply from the parent tree.

Trees that are cut during the dormant period will sprout much more vigorously than those cut during late spring and summer. This is because the reserves of carbohydrates in the roots are at a maximum during the winter and at a minimum immediately after the formation of new leaves and shoots (Kramer and Kozlowski, 1979; Larcher, 2003). If cuttings are made late in the growing season, sprouts sometimes appear almost immediately, but they rarely harden before the first frost. Therefore, coppice cuttings are best done after leaf drop in late fall or winter. Interestingly in some species such as oak, as the tree increases in bole diameter and age, the ability to sprout becomes weaker (see a description of why, under stump sprouts, below). This becomes obvious when a small-diameter young oak stand is cut and vigorously re-sprouts as compared to an older, larger-stemmed oak which does not.

If full advantage is to be taken of vegetative reproduction in renewing a stand, all the trees of the species to be reproduced should be cut in one operation to stimulate sprouting to the utmost. Trees of the same species in a single stand are often interconnected by root grafts. Therefore, if a few scattered trees are left behind, they may draw on the food supply of the common root system or contribute hormonal inhibitors of sprouting and thus reduce the vigor of the new sprouts. The reduction is often greater than could be caused by the shade of the residual trees.

Although trees of vegetative origin grow faster during early life than those developing from seed, they do not retain this advantage on long rotations. Vegetative reproduction generally attains larger size on a short coppice rotation than trees grown from seed would in the same time. That is the primary advantage of coppicing stands on short rotations. If the rotations are extended over a much longer period of time to produce sawlogs, there appear to be no consistent differences in size related to the mode of origin (Leffelman and Hawley, 1925; Bellingham and Sparrow, 2003).

Types of Vegetative Regeneration

The generalizations apply to most stands that are regenerated vegetatively, but there are some important differences between several forms of vegetative regeneration.

The forms of vegetative regeneration can be categorized as: (1) **stump sprouts** from dormant buds; (2) **stool shoots** or **sprouts** (mainly from adventitious buds); (3) **seedling sprouts**; (4) **lignotubers**; (5) **root sprout** or **suckers**; and (6) **layering**.

Stump Sprouts Originating from Dormant Buds

Stump sprouts usually arise from dormant buds at the root collars of tree stumps (Fig. 12.2). These shoots almost invariably develop from lateral buds that were originally formed on the leading shoot of the seedling; these buds did not develop into lateral shoots but remained dormant, growing outward with the **cambium** to maintain positions just beneath the bark (Dirr and Heusser, 2009). The pith of **dormant buds** can be traced all the way back to the pith of the original stem. If this connection is broken during the growth of the tree, the bud becomes incapable of developing into a new shoot. If the bark over the dormant bud becomes too thick, it may be impossible for the bud to break through and develop into a sprout. Both the thickness of the bark and the possibility of interruption of the bud trace will increase with age. Thus, the sprouting capacity of the tree tends to decline with age and size.

Dormant buds produce new shoots at any level on the bole, although only those that arise at or very close to the ground line have much potential for developing into good trees. Trees that develop from sprouts that originate too far aboveground are often crooked, forked, or subject to breakage. **Epicormic branches** are usually sprouts that are released dormant buds that develop even higher on the living boles of trees. Stump sprouts usually cluster in dense rings around sprouting stumps. Their numbers usually dwindle rapidly because of severe competition between them. The sprouts begin from lateral buds, so they must curve upward as they develop into main stems.

The risk that rot will spread from the old stumps to the heartwood of the new shoots varies with species. It does not appear to happen in such diffuse-porous species as the maples in which any infected interior of the trees is "compartmentalized" or sealed off from the sapwood by gum formation (Shigo, 1984, 1985). However, rot will spread from old stumps with other diffuse–porous species, such as yellow-poplar. With oaks, the incidence of such rot increases with the diameter of the parent stump and the distance of the sprout aboveground (Roth and Hepting, 1943; Ranius and Jansson, 2000). However, American oak forests have many large, sound trees that grew so rapidly when young that they must have been of sprout origin (Lamson, 1976). There seems to be no problem of rot with vegetatively sprouted

(a) (b)

Figure 12.2 **(a)** Dormant buds on beech can be seen as small dots (protuberances) on the smooth gray bark. **(b)** Released dormant buds (epicormic sprouts) on ash. *Source:* **(a, b)** Mark S. Ashton.

coast redwood, which produces sound, straight sprouts from gigantic stumps (Brown and Swetnam, 1994) (see Fig. 12.1).

The sprouts of conifers come from dormant buds that form at the base of either primary or secondary needles. Among the conifers that can be usefully regenerated by stump sprouting are coast redwood, bald-cypress, and several pines, including shortleaf, pitch, pond, and certain Mexican species.

Stool Sprouts

Stool sprouts, usually crooked and slow growing, develop from stumps that have been cut so often over so many decades, that they have callused over with injury tissue originating from the cambium and bark (Fig. 12.3). Such stumps or **stools** may have spread to be several feet (1 m) in diameter, and resemble the mysterious burls that sometimes form on tree stems (Rackham, 1998). Most of

(a)

(b)

Figure 12.3 (a) Stool sprouts from an ancient stool of a European white oak coppice managed for several hundred years on a short rotation for firewood and fence posts in southeast England, UK. Note the breadth of callus tissue. **(b)** An ancient oak coppice of over 500 years in Devon, southwest England. *Source:* **(a, b)** Mark S. Ashton.

the sprouts arise from **adventitious buds** and only some are from released dormant buds. The proportion of dormant buds obviously decreases with each succesive cutting and the increased spread of callus that expands the stool. Adventitious buds arise after the injury to the cambium and originate within the callus or injury tissue itself. Adventitious sprouts therefore all originate at the actual site of the injury (the severed stem) and can be identified right at the edge of the cut stem. Thus sprouts are often less than 1 in (2.5 cm) apart when they start, and the competition between them is so intense that none can support themselves adequately. Their height growth is stunted and they remain crooked even after natural thinning has greatly reduced their numbers.

Stool sprouts of dormant-bud origin are thus more vigorous than those of adventitious-bud origin because they are directly connected to the vascular system before injury and remain connected when released, making them both stronger and more rapid growing. The dismal reputation of the coppice system in countries where stands have been coppiced at short intervals for very long periods (500–2000 years) has come chiefly from the fact that over successive cuttings, most of the stumps developed into burl-like stool sprouts of mostly adventitious origin. The rare cases in which such stumps have developed in the United States, such as the dwarf pitch pines of the Pine Plains of New Jersey, have resulted more from frequent forest fires than from fuelwood cutting.

In a few species, including American beech, adventitious buds produce sprouts that are called **stool shoots**. These sprouts arise between the bark and wood around the tops of stumps. They are usually short lived, and they do not have any real importance for tree growth.

Seedling Sprouts

Vegetative sprouts that come from the root collar of small seedlings and saplings are called **seedling sprouts**. They are defined as coming from stumps less than 1 in (2.5 cm) in diameter. This particular source of regeneration is much more important with the shelterwood methods of regeneration than with the coppice method. Simple coppice rotations are often too short to be reproductively mature enough to produce the kind of seed quantity that would, over some years, allow for this kind of regeneration to develop. In addition to oak seedling sprouts that develop after injury or fire, many pine species such as short-leaf pine and the Montezuma pine of Mexico have similar regeneration sources (see Chapter 10, Box 10.2).

Lignotubers

Many of the Australian eucalypts, which are planted widely in the warmer parts of the world, have such a co-evolution with fire that they have some special modes of sprout regeneration (Noble, 2001). The mode that is largely limited to this genus is the **lignotuber**. Lignotubers are paired globular masses of tissue, full of buds that form in the axils of the opposite leaves of small seedlings (James, 1984) (Fig. 12.4a). These tissues grow much larger but usually become buried at the base of the tree stems as swellings. If the stems do not get more than about 8 in (20 cm) in diameter, sprouting from the lignotubers is prolific when the tops of the trees are cut, killed, or damaged.

Many species of eucalypts also have typical dormant buds that form in the leaf axils and produce stump sprouts or epicormic branches. However, some of the most important members of the genus do not sprout but respond to infrequent catastrophic fires by mass seeding.

Root Suckers

Sprouts can also arise from adventitious buds that sometimes develop in the callus tissue that forms over wounds or in the root cambium of a limited number of tree species. Several hardwood species that produce **root suckers** or **root sprouts** along the roots of trees occur after the above-ground portion of the tree is killed or even slightly damaged. Root suckers are so prevalent in the aspen poplars that true seedlings are rare in many localities (Schier, 1978; Frey *et al.*, 2003). It is also common with sweetgum, blackgum, American beech, black locust, and sassafras. Trees that arise from root suckers can grow much better than those from stump sprouts. The shoots are much more likely to be free of rot, as well as evenly spaced and straight, because they are not clustered around stumps. Root suckering in some species, such as American beech, can be so effective that it out-competes other species, such as sugar maple, that are reliant upon advance reproduction in the understory. In many instances where beech has been affected by beech-bark disease, it has become a never-ending cycle of canopy dieback and understory suckering to the exclusion of almost everything else (Fig. 12.4b).

Layering

This kind of vegetative reproduction arises from living, low-hanging branches that have been partially buried in moist organic matter. Layering occurs mainly in peat bogs where sphagnum moss tends to overgrow the lower branches of trees in open stands (Dirr and Heusser, 2009). Layering can also occur in mountain forests near the treeline, where the prostrate form of the tree caused from wind and the weight of the snow promotes many conifers (e.g., subalpine fir, Engelman spruce) and shrubs (e.g., Sitka alder, dwarf willows) to spread outward (Fig. 12.4c). Finally, many forest understory shrubs spread by layering to form dense thickets (e.g., rhododendron, laurel) when branch ends are buried beneath leaf litter. Artificial layering is one of the vegetative propagation techniques of inducing branches to form roots so the branches can be severed and planted.

Figure 12.4 **(a)** Lignotubers appear as swellings at the base of the root collar on this Eucalyptus sapling. *Source:* E. L. Barnard, Bugwood.org. Reproduced with permission from Bugwood.org. **(b)** Root suckers on American beech. *Source:* Mark S. Ashton. **(c)** Layering of prostrate branches of Japanese stone pine (*Pinus pumila*) above tree line, Japan. *Source:* P. Ashton. Reproduced with permission from P. Ashton.

Simple Coppice Systems

Stump-Sprout Stands

The most common kinds of coppice stands are those that arise from clusters of sprouts such as stumps or stools. These typically arise as absolutely even-aged stands after simple coppice cutting in which all the trees are cut, so that nothing is left to reduce the vigor of sprouting (Fig. 12.5). If this coppice cutting has been repeated at short intervals for many decades, the most vigorous sprouting species usually comes to predominate, but if, as in the eastern deciduous forests of the US, the cuttings have not been frequently repeated, the stands are of mixed species that sprout, such as maple, hickory, and oak.

The congested nature of sprout clumps restricts what can be done with the simple coppice system. The rotations must usually be shorter than those used for the production of good sawlogs. Ordinarily, the objectives are to grow either fuelwood, pulpwood, biomass, animal browse, or small wood products (e.g., poles, fencing, basketry) (Fig. 12.5). Coppice systems have therefore long been associated with agriculture and farming.

The spacing of a coppice stand derived from stump sprouts is controlled by the arrangement of the parent trees. If the rotation is long enough to produce sawtimber, many of the original sprout clumps will die of suppression. If reproduction depends on the simple coppice method, the new sprout clumps will grow up so far apart that production suffers. Best results are obtained when the rotation is short enough that the final spacing of sprout clumps is acceptable as an initial spacing for a new coppice stand. The vigor of sprouting from stumps also declines rapidly with increasing age and diameter. The period of satisfactory sprouting is usually coincident with that of most rapid growth and may end before the trees become effective seed bearers (Fig. 12.6).

During the harvesting process, attention must be given to suitable preparation of the stumps. Saws are better than axes for cutting, and most other tools are likely to loosen the bark of the stumps. It is reputed to reduce incidence of rot if the cut surfaces are slanted so that water runs off them. Normally, it is best to cut the stumps as low as possible so that the new sprouts will not have to grow on the side of a decaying, unstable stump (see Fig. 12.3). Sometimes the deliberate use of slash burning to kill the sides of the stumps is useful in restricting the sprouting to buds at or below the ground line.

If repeated crops are to be secured from stump sprouts, the rotations are ordinarily less than 35 years and sometimes only 1 or 2 years long. The logical rotation length is one which will maximize mean annual increment for the dimension of the product in question, which includes small saplings for basketry (2 years), and poles for

(a)

Figure 12.5 Simple coppice systems. **(a)** Hazel on a 2-year rotation for basketry in southwest England, UK. *Source:* Mark S. Ashton.

(Continued)

Figure 12.5 (Continued) **(b)** Red maple stump sprouts on a 15-year rotation for firewood in Connecticut, US. *Source:* Yale School of Forestry and Environmental Studies. **(c, d)** *Cryptomeria japonica* on a 45-year rotation for construction and artisanal timber within private woodlots of Japanese farmers in central Japan. Midway through the rotation plastic beads are wrapped around the boles to impress a pattern on the outside wood for ornamental and cultural purposes in woodworking. *Source:* **(c, d)** P. Ashton. Reproduced with permission from P. Ashton.

fuelwood or fencing (25 years) (Box 12.1). With this system, the form of the stems is usually so poor that these are the only products intentionally grown under the simple coppice method. After several rotations it is desirable to obtain some reproduction from planting or natural seeding to replace old root stocks and improve the spacing. This kind of restocking can sometimes be encouraged by thinning the coppice stand in the rotation.

Another important objective of any thinning is the reduction of the number of sprouts in a clump; the faster this number can be reduced to one, the better is its growth. In places such as certain sal forests (*Shorea robusta*) of India, where there is overwhelming demand for fuelwood, this procedure can be used to reserve some stems to grow to pole sizes for structural material while the remaining wood is taken for fuel.

Figure 12.6 Stand of 8-year-old red maple stump-sprouts at the Yale–Myers Research and Demonstration Forest in Connecticut, US, showing the typical form and spacing of a short-rotation coppice stand. *Source:* Yale University School of Forestry and Environmental Studies.

Box 12.1 Ancient coppice systems from the past: Sri Lankan *Syzygium* coppice for producing high quality steel from the 7^{th}–11^{th} centuries.

In southwest Sri Lanka the monsoons occur twice a year, from October to November and from April to July. However, on the far eastern side of this southwest region, the hills rise up inland above the coastline. Winds are dry, bringing no rain. Archeologists have found the ruins of over 41 furnaces that smelted high-quality carbonized steel and have surmised it was these dry monsoonal winds that fueled this process by creating a natural wind-pressure effect. This metal was traded across the world, but especially in the Middle East, for the creation of Damascus swords during the 7^{th}–11^{th} centuries. The charcoal that was used came from coppice of *Syzygium* spp., a tree that sprouts rapidly (Fig. 1). The forest around these sites is all of coppice origin. It is low statured, unstratified, and mono-dominant. The normal forest type for this region would be stratified and high statured with representation of non-sprouting dipterocarps.

Box 12.1 Figure 1 Low forest comprised mostly of coppiced Syzygium. *Source:* Mark S. Ashton.

Root-Sucker Stands

The coppice system functions at its best in the management of species that can regenerate as stands of rather uniformly spaced sprouts from root suckers. Regenerating species that produce root suckers is even simpler than creating a new crop from stump sprouts; in fact, it is usually too abundant. The stands are not only even aged but also single species, and can be managed that way. Sprouting is not confined to the stumps of the original stand, so spacing is not a problem. Also, no care is necessary in ensuring that the stumps are severed uniformly to induce sprouting. The tree stems are usually straight, and there is no evidence that the ability to produce root suckers declines with age. The maximum length of the rotation is determined by the same criteria that might apply to a pure plantation.

Among the species that regenerate from root suckers are the aspen poplars, sweetgum, beech, and black locust, as well as many species of shrubs and other understory trees. By far, the most important are the quaking and bigtooth aspen poplars, especially in the Great Lakes Region (Whitney, 1987) (Fig. 12.7). Vast aspen forests replaced

(a)

(b)

Figure 12.7 **(a)** A well-stocked stand in Chippewa National Forest, Minnesota, of 4800 aspen root suckers per acre, which originated after a single coppice cutting made during the dormant season 11 years previously. *Source:* US Forest Service. **(b)** One-year-old aspen coppice regeneration, Wasatch-Cache National Forest, Wyoming, US. *Source:* D. Page, Bugwood.org. Reproduced with permission from D. Page.

the virgin stands of pine and hardwoods after they were devastated by heavy cutting and fires near the beginning of the present century, due to prominent root suckering (Whitney, 1987; Mladenoff and Pastor, 1993).

A large and diversified wood industry now subsists on coppice management of aspen in the US upper Midwest. This works best on the better soils where the trees can grow to middle age with good diameters before the heart-rotting fungi harm them. Soils that are excessively wet or dry are best converted back to conifers. Aspen regeneration from root suckers depends mainly on being sure to have cut every tree down, preferably during the dormant season (Bates, Blinn, and Aim, 1993). As is true of other sprouting species, the regeneration step is simple and almost automatic. However, failure to regenerate can often be attributed to overbrowsing, because sprout growth is highly desired by both livestock and game, such as elk and deer.

Planted Coppice Stands

There is no fundamental reason why the stands intended for coppice management cannot be created partly or completely by planting. This actually has two very important advantages. It enables the growing of successive crops from one investment in plantation establishment, and it preserves the genetic constitution of the planted trees for many rotations. Some stands that have been coppiced for centuries in England were originally planted, and the initial root stocks have survived that long (Peterken, 1997; Rackham, 1998). Currently, some of the most intensely managed coppice stands have used improved stock of cottonwood and other fast-growing trees that are subsequently managed on a 3–5-year coppice rotation for biofuel and pulp (Dickmann *et al.*, 2002) (Box 12.2).

Wood Pastures as Coppice Stands

When trees are routinely cut at about 6 ft (2 m) or more, such that dormant buds are released at the top of the bole to produce sprouts, the young regrowth is inaccessible to browsing animals. This can be a very successful technique for integrating pasture and livestock into woodlands that are managed for firewood, fodder, and other sprout-dependent products (Kirby *et al.*, 2008). **Pollarding** is the term for cutting the boles of trees at

Box 12.2 Intensive coppice management of improved hardwoods for biomass and biofuels.

Historically, biomass harvests have mostly been a by-product of the US forest industry's timber and pulpwood land management. Because of this, the current forest industry in the US and Canada are the largest producers of energy from renewable sources for their respective countries, more than either wind or solar. Biomass has also been harvested in southeastern second-growth hardwood forests as a by-product of timber harvesting since about 2005. Most of the trees that are cut are taken lengthwise and dragged to a roadside chipper, and then taken to a processing mill where the chips are made into wood pellets, and exported to Europe. This is probably not very sustainable on much of the land, given the kinds of poor hardwood sites and the low growth rates.

Biomass plantations as the focus product have been in trial research for several decades (since the oil embargo of the 1970s). Regions of focus have been in the southeastern states, lakes states, and Pacific Northwest. American companies, in collaboration with the government, have been exploring the use of sprouting species such as cottonwood (hybrid poplar), sweetgum, sycamore, yellow-poplar and eucalyptus. All of these species can be grown on very short coppice rotations. For this method, soils must be tillable, relatively fertile, flat, and usually irrigated. To start a coppice for poplar, planting is done with cuttings at a density of 1500/acre (~600/ha), but range between 700 and 5000/acre (~280–2025/ha) (see Table 1 for yields). For comparison, pulpwood plantings for poplar are usually wider at a density of 300–400/acre (~120–160/ha) (Townsend, Kar, and Miller, 2014). The plantations are harvested on 6–10-year rotations. Other promising species, especially eucalyptus (Fig. 1) and sweetgum are being investigated as possibilities for poorer sites where poplar does not do as well.

Box 12.2 Table 1 A comparison of production estimates of hybrid poplar from different regions of the United States. The variation is due in part to the different clones tested.

Region	Production estimates (dry ton/acre/year)	Growth cycle (years)	Sources
Lake States	1.25–3.35	5–8	Miller and Bender, 2012
Upper Midwest	2.45–5.13	13	Zamora *et al.*, 2013
Mississippi River Valley	2.01–2.99	8–10	Zalesney *et al.*, 2011
Pacific Northwest	3.08–8.61	6-11	Berguson *et al.*, 2010

Source: Mark S. Ashton.

(Continued)

Box 12.2 (Continued)

Box 12.2 Figure 1 This 24-month-old stand of cottonwood trees is being grown in the Mississippi Delta. *Source:* Mark S. Ashton.

this height and promoting sprout growth. This technique is ancient and is often associated with common land, where the trees of woodlands are susceptible to browse from open-range livestock. Some of the most ancient systems that can still be seen are in the Basque Country of northern Spain (Cousins and DuVal, 2012) and in parts of southern England (Peterken, 1997) (Fig. 12.8).

Variants of pollarding can be found across the world. For example in the Himalaya of India, the evergreen oaks of the middle hills are both an important source of fodder and fuelwood for villagers as well as timber for the state (Awasthi *et al*., 2003). Law permits the routine lopping of side branches to encourage regrowth, but the main stem must not be severed until the tree is cut for sawtimber by

(a)

Figure 12.8 Pollarding. **(a)** Ancient pollarding of beech woodland in the Basque region, Spain. *Source:* Mark S. Ashton.

(b)

(c)

Figure 12.8 (Continued) **(b)** Shredding of evergreen oaks (trees in the foreground with columnar crowns and epicormic shoots along the bole) in the foothills of the western Himalayas, India. *Source:* P. Ashton. Reproduced with permission from P. Ashton. **(c)** Pollarded linden trees, Olway Mansion, UK. *Source:* T. Joliffe. Reproduced under the terms of the Creative Commons Attribution ShareAlike licence, CC_BY-SA 2.

the state (Fig. 12.8). The ancient practice of pollarding has also become very much a part of urban street-tree cultivation, particularly in Europe, where street trees that have crowns too large for the space are routinely pollarded to confine their crowns (Fig. 12.8)

Hedgerows as Coppice Stands

The ancient cultivation of hedgerows, particularly in southern England and in western France (Brittany), are essentially coppice systems. Originally planted in

lines, species that have a profuse ability to sprout such as hawthorn, oak, chestnut, and beech, were cut clear to the ground every few years to promote an inpenetrable barrier for livestock. These practices have been sustained in some cases for several thousand years to the extent that the hedgerows have become earthen mounds that now prevent soil erosion (Peterken, 1993) (Box 12.3).

Box 12.3 The coppice management of ancient hedgerows in the UK.

Hedges and hedgerows have an ancient history in many parts of Europe. Written history records such hedges as far back as the first century BC, and archaeological evidence indicates prehistoric use. By 800 AD in the UK, hedgerows were commonplace. There are many styles of hedges and they have been called many different names: hedges, hedgerows, and fencerows. To many people, hedgerows are often thought of as unmanaged trees, shrubs, and vines that have grown up on the boundary of a field due to neglect. In fact, many hedgerows were often planted and maintained for centuries.

The most common trees used for ancient hedgerows in the UK are hawthorn, oak, apple, willow, ash, elder, alder, maple, and elm. Hedgerows comprised of these trees were often planted and established in a non-wooded area. Hedgerows formed of trees left behind after clearing a forest were comprised of more shade-tolerant, woodland trees. Hedgerows were used to confine livestock, exclude unwanted wild animals, and in some cases provide a defense from cavalry. Almost all hedgerows were used as a source of firewood.

Establishing a living hedgerow often makes use of a temporary fence consisting of stakes and trouse (cut branch wood). Trouse and flexible cut wood are interwoven between the driven stakes. The hedgerow plants are planted along this temporary fence. The temporary hedgerow, especially the trouse, protects the young seedlings from being browsed. Once the hedgerow trees begin growing, it needs hedgelaying, also known as plashing. Plashing a hedgerow creates an impenetrable barrier of living branches by bending the stems towards the ground and interweaving their branches. In the dormant months, the main stem is partially cut, laid horizontal, and interwoven with neighboring stems. In subsequent years, the plashed stems send branches growing vertically. To prevent these stems from becoming too large and turning the hedge into a row of large coppice-origin trees, continued hedgelaying is required. Once established, gaps that formed in the hedgerow would be mended with trouse, plashings, and transplants. Hedgerows have provided, and still do provide a sheltered place for additional trees and plants to become established and thrive.

Not only were hedgerows maintained as stock barriers, but they were also used as a source of firewood. Trees were coppiced or pollarded to provide a steady supply of fuel. Pollarding firewood trees kept their new growth beyond the reach of nearby livestock. These trees were cut every 10 years or so, and the sprouts, still attached to the large root system, would vigorously grow. This process could be repeated for decades and even centuries. In hedgerows throughout Britain, living coppice stools can be found that are over 800 years old.

Box 12.3 Figure 1 An old plashed hedgerow in Somerset, UK. *Source:* M. Ashton. Reproduced with permission from Mary Ashton.

Box 12.3 (Continued)

Box 12.3 Figure 2 **(a)** A newly plashed hedgerow where the coppice from prior growth is almost completely severed, lain down, and interweaved with other cut stems. The partial connection promotes the re-sprouting of new coppice shoots along the stem to create the new hedgerow. **(b)** An example of a new hedgelaying with its by-products of firewood and kindling in Somerset, UK. *Source:* **(a, b)** M. Ashton. Reproduced with permission from Mary Ashton.

(a)

(b)

Coppice Systems with Irregular Structures and Age Classes

Simple Coppice with Standards

The most ancient example of stands in which different species are grown on rotations of different lengths are those managed on the **coppice-with-standards system** in which small numbers of scattered promising trees, or **standards**, are reserved above sprout-coppice stands and left to grow for two or more short coppice rotations. The standards are usually of different species from those grown as coppice sprouts, but they can also be of the same species. Ordinarily there are several age classes of standards usually constituting a multi-aged stand (Fig. 12.9); such stands are sometimes called **compound coppice stands**. This system evolved in places such as Europe, before coal became the predominant energy source; it was important to combine the production of large amounts of fuelwood with that of some larger trees for construction.

The trees reserved for standards are usually dominants of good form and are usually of seedling origin that would be classified as advance reproduction. The sprouts that arise after the cutting will form a distinct understory, beneath and between the standards. The number of standards in a given age class is gradually decreased by the harvesting in the successive coppice rotations.

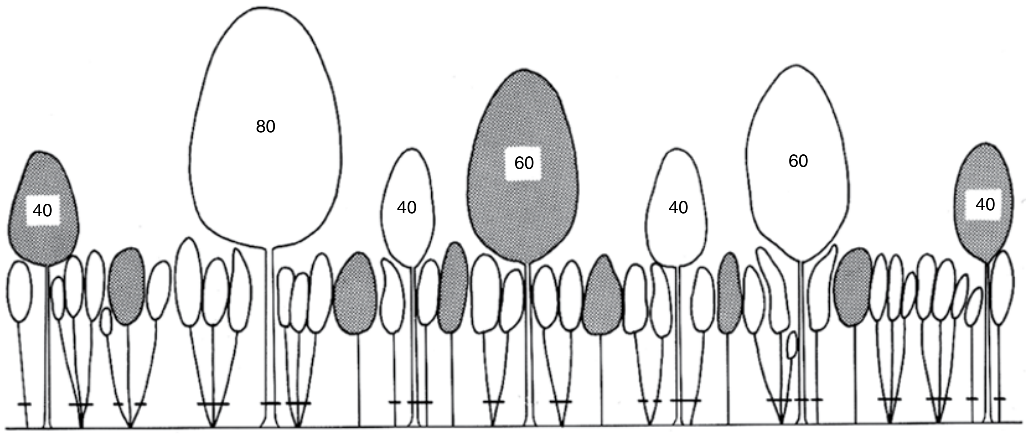

Figure 12.9 A compound coppice, with two age classes of standards, at the end of a 30-year coppice rotation. All trees of the coppice stratum will be cut except those (*shaded crowns*) chosen for new standards. The 60-year-old standard has reached the end of its assigned rotation and will be cut. The cutting of younger standards is an operation analogous to thinning by which the number of standards in a particular age class is gradually reduced with advancing age, just as in a balanced, all-aged stand. *Source:* Yale University School of Forestry and Environmental Studies.

When the old standards are finally harvested, their stumps may be too large to sprout, and they may have to be replaced by planting or natural seeding from the remaining standards. Cleanings are sometimes necessary to bring young prospective standards of seedling origin up through the competition of the faster-growing stump sprouts. The growth of well-established seedlings can also be accelerated by cutting them back to the ground and converting them into seedling sprouts. Plants of this type have the rapid initial growth of true sprouts, combined with the good form and rot resistance of trees of seedling origin. If the seedling sprouts spring up in pairs or clusters, only the best ones should be retained.

Intolerant species with light foliage are usually favored as standards, while trees capable of thriving under partial shade are desirable in the coppice. The species of the coppice must sprout readily and produce wood that is merchantable in small sizes. The standards do not have to be of species that sprout; thus, a conifer can be grown over a hardwood coppice and can be introduced by planting if necessary.

Generally, the trees that are standards are sufficiently isolated to develop deep crowns so that their rather short boles grow rapidly in diameter. If the crowns expand rapidly enough, this usually inhibits the development of epicormic branches, which can cause problems after any kind of partial cutting with most hardwoods and some conifers. However, if the coppice sprouts grow fast enough, they may eliminate any epicormic branches that have formed and may help keep the boles of the standards free of new ones. Dominant trees with full, vigorous crowns are less likely to develop epicormic branches after exposure, than those that have unhealthy crowns or are from lower crown classes.

Like the simple coppice system, in coppice with standards most of the production goes into small sprouts that are useful if there is demand for fuelwood, pulpwood, or other small wood products, rather than fine sawtimber. This is why, with the decline in demand for wood energy and small wood products, stands of this kind fell into disfavor in Europe and are grown only in rare cases in America (Fig. 12.10). Nevertheless, there may be important uses for them in cases in which demands for fuelwood, pulpwood, or animal browse impinge on the use of forests to grow larger timber, especially on smallholdings. With current green energy issues, coppice and coppice with standards may again become economically feasible.

Coppice stands are almost always dealt with as being even-aged, but there is no basic reason why patches of sprouts of different age should not be intermingled in all-aged stands by the **coppice selection** method. If the object is to include production of some large trees, then the coppice-with-standards system is more appropriate.

Wood Pastures and Hedgerows with Standards

In the same manner, a coppice-with-standards method can be incorporated into wood pastures and hedgerows. The trees are largely unpruned and because of the open nature of both systems, standards are tall, large-crowned, and spreading. Standards selected in hedgerow coppice are often trees of value for ornamental, wind-break, or shade uses, selected by the farmer or forester to protect livestock or agricultural crops (Peterken, 1993). In western Europe many of these trees were elms, oaks, and beech, all of which can provide shade and cover for livestock in adjacent fields. In other circumstances, windbreaks, in particular, can be conifers which, when pruned, can be harvested for their timber, and because they are evergreen, they serve well as windbreaks for livestock.

Figure 12.10 A recent cutting of an oak coppice in the Spessart oak region of Bavaria, Germany. Two classic German foresters in their attire are shown for scale. The coppice, which has been cut periodically for fuelwood, has been used to control the form and pruning of the standard. There are at least three age classes of standards shown here. The foresters stand next to the oldest, those that are young sawlog in size (8–10 in, 20–25 cm DBH) are next, and the youngest are pole size. Note through thinning there are fewer and fewer standards for each increase in age/size class. *Source:* D. B. Kittredge. Reproduced with permission from D. B. Kittredge.

Radiata pine in New Zealand is often used for this purpose in sheep pastures.

Natural Layering as a Vegetative Regeneration System

In the peat swamps of northern boreal forests, regeneration by layering of black spruce and northern white-cedar is an important supplement to regeneration from natural seeding (Morin and Gagnon, 1992; Paquin and Doucet, 1992; Greene *et al*., 1999). Although these species produce seed in abundance, a high proportion of the seedlings are suppressed by the relatively fast-growing sphagnum moss, which is the main constituent of the groundcover. The seedlings have the best chance of survival on scattered, elevated hummocks and on decaying wood, a seedbed that is often lacking in the managed forest. As time progresses, the peat grows up and engulfs the bases of the trees, covering any low-hanging branches that remain alive. The adventitious buds of buried portions of the branches develop into roots, while the living ends of the branches turn upward and grow into separate trees. Young shoots of this kind are sturdier and more vigorous than seedlings, but their form is not as satisfactory (Greene *et al*., 1999).

Reproduction of black spruce by layering is most readily achieved in peat bogs by the use of a modified single-tree selection cutting (Johnston, 1977; Bergeron *et al*., 1999). If continued reproduction from layers is to occur, the uneven-aged form must be maintained so that the living crowns of the trees will remain in contact with the ground long enough for layers to become firmly rooted. It is significant that the residual stands are surprisingly resistant to wind, because the peat is so resilient that the force of the wind tends to be dissipated in agitating the soil itself rather than in damage to the trees. However, black spruce growing on the firmer soils of uplands lacks windfirmness so it rarely layers. It is best reproduced by clearcutting after advance regeneration has become established or by planting.

In northern white-cedar, reproduction from layers is fully as important as that from seed. Although normal layering from low-hanging branches is the most common form of vegetative reproduction, the new, upright stems can also develop from the branches of windthrown trees. Appreciable amounts of reproduction may also rise from the rooting of small branches that become partially buried after being severed from the parent tree by browsing animals or during logging. The species is important not only for the production of posts and poles but also as a favored winter food of deer.

The Role of Coppice Stands in the Past, Present, and Future

The chief role of the coppice system is in growing fuelwood, pulpwood, and other products of small trees from sprouting species of angiosperms. Provided that the species is one that sprouts, no regeneration method has

a higher certainty of success. The start of the next growing season is the only delay; the growing space of the soil remains almost continuously and completely occupied. The new stems grow astonishingly fast in height, so that the aboveground growing space is quickly reclaimed. The rotations are generally confined to the short periods during which accumulation of total dry matter is most rapid. The optimum rotation length is usually regarded as that which maximizes the mean annual increment of dry matter. Although the trees are seldom impressive in size or appearance, the return on the small investment in growing stock is very high and it may be obtained in a short period.

Past Uses of Coppice Stands

For centuries, coppice methods of regeneration have been the most efficient way of growing crops for fuelwood. Because this has always been the most important human use of wood, it may be presumed that the coppice system has always been the most common kind of silviculture. This was true for many centuries in much of Europe and for the 18th and 19th centuries in parts of the Atlantic seaboard of the US. The availability of cheap coal and later, oil, caused the situation to change during the first half of the 20th century. In both Europe and the US, coppice-origin forests have been replaced with high forests. However, there is one noteworthy past difference between the continents: in Europe and elsewhere in the Old World, the coppice system developed a bad reputation because repeated coppicing from the same root stocks with short rotations was associated with declines in the quality and vigor of successive crops. Coppicing was repeated so long and so often that all the stands in vast areas degenerated to grotesque clumps of crooked stool sprouts. Some problems came from depletion of the inorganic nutrient capital of the soil. Further problems resulted from the nearly complete utilization of the forest production, including litter gathering, that is often associated with coppicing.

Foresters in the US were for some years convinced that what they saw in the so-called Sprout Hardwood Region (see Fig. 12.5) of the Boston–Washington megalopolis, was the same sort of degraded coppice forest about which they had read in the European literature. However, coppicing in the American cases had usually not been repeated more than two or three times before the collapse of the fuelwood market caused it to cease. Early in the 20th century, it was possible to see many potential deformities in the multiple-stemmed sprout clumps in the aging stands that had once been coppiced for firewood. However, unlike Europe, true coppice stools covered with deformed sprouts were so rare as to be curiosities (see Fig. 12.3). Now that most of these trees have grown to sawlog-size and the old sprout clumps have thinned themselves down to single stems, it is difficult to determine the origin of these trees. The fine standard shown in Fig. 12.9 was actually of stump-sprout origin.

The coppice method is associated with the kind of close utilization and frequent cutting that is most likely to remove chemical nutrients from the site and thus cause their depletion. This is true whether twigs are being removed for fuel by labor-intensive means or whether they are chipped for pulpwood under circumstances in which the labor needed for manual delimbing is too costly. The losses can be reduced to some extent by measures such as harvesting trees when they are leafless, or delimbing or debarking by the stump and thus leaving the twigs, leaves, and branches on the site. If the depletion becomes too great, it may be necessary to apply fertilizer.

Another difficulty that is historically associated with the coppice method is that of changing from short rotations to long rotations, if the coppice method has to be replaced with high-forest methods. If, as was once the case in southern New England, large areas are coppiced every 30 years and it becomes necessary to switch to sawlog management with 80-year rotations, the situation becomes very awkward. During the 50-year transition period, it is possible to have large areas of forests but few trees large enough to harvest. Circumstances of this kind were part of the reason why European foresters have cursed the coppice method for so long. Foresters who have inherited such situations are likely to take dismal views of short rotations.

Present and Future Uses of Coppice Stands

Currently, coppice methods remain an important system in many developing nations. In developed nations, there has also been a resurgence of interest, if not practice, with issues of climate change, biofuels, and renewable energy. One virtue of the coppice method is that it preserves the genetic attributes of any trees grown by it. This attribute is often used in the culture of various poplars not only by coppicing but also, at least with the cottonwood poplars, by the planting of cuttings that easily take root. If a genetic form of chestnut could be developed to replace the ill-fated American chestnut, it would be logical to grow it by the coppice method to perpetuate whatever planted genetic combination was necessary. Fortunately, this species sprouted vigorously even from large stumps and grew rapidly into stems that are suitable for sawlogs and rot-resistant telephone poles.

It would be theoretically possible to use the coppice system to grow almost any American hardwood and the few sprouting conifers listed earlier. It might be

done in cases representing special or particular kinds of circumstances. It would be the logical system to follow in order to obtain domestic fuel for a single household entirely from a woodlot of several acres (hectares). A paper company might use it as a means of providing a supply of hardwood pulpwood that was always readily available, regardless of mud conditions, from lands close to the mill. Coppicing is a very useful way of producing browse and low cover for some wildlife species, especially those herbivores that are such important game species. One important and traditional use of the coppice system is for the production of round posts and small poles from such species as black locust.

From the aesthetic standpoint, coppice cutting can be even worse than clearcutting. The cutover areas have the same appearance, and the harvests are repeated more often than is the case with true clearcutting. On the other hand, the new vegetation covers the land more quickly. Most of the species do not grow very tall, and they produce monotonously regular supplies of fuelwood and fodder. Sometimes they are so low statured they seem little different from brushfields.

Conversion of Coppice Stands to High Forests

Although the coppice methods have an important place in silviculture, much of the forester's concern with coppice stands is to replace them with stands of seed origin. The very same sprouting habit that makes coppice stands easy to regenerate also makes them hard to eradicate. The degenerate coppice stands of Europe have been a classic problem.

The most serious North American problem of this kind has to do with stands of sprouting woody plants that are not normally regarded as coppice stands. These are the extensive brushfields of shrubs or poor hardwood species that have developed after heavy cutting and repeated fires on soils that are best adapted to the growing of non-sprouting species of conifers. On many of these sites, conifers grow well and broad-leaved plants grow badly, but the conifer seed source has been eradicated. Fortunately, the development of herbicides and mechanical methods of site preparation has made it much easier and cheaper than it once was to eliminate the sprouting species and restore the better ones by planting. In these situations, prescribed burning by itself is seldom helpful, although it can be useful in conjunction with chemical and mechanical methods.

In the case of formerly coppiced hardwood stands in the eastern US, there has been reason for replacement chiefly on sites where conifers would grow better. If the soils are good enough for the hardwoods to grow well, it has generally been appropriate to let the stands grow and to thin them while the crop trees grow to sawlog size. Shelterwood cuttings can be used for ultimate regeneration of the stands, although both seedlings and sprouts can be anticipated in the ultimate regeneration. However, some of the regeneration will also come from stump sprouts. As is the case with vegetative regeneration in general, the question of whether this is good depends on the characteristics of the sprouts and not on some ancient dictum about the relative merits of sprouts and seedlings.

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13

Natural Regeneration: Selection Methods

Introduction

This chapter describes the conceptual approach to the selection system with a focus on the selection method of regeneration, its uses, and the problems that may arise from its use. The social and ecological circumstances are described as to how and where the method might be applied. Descriptions of the different approaches to selection systems will include: single-tree, group, patch, and strip methods, with discussions of their advantages and disadvantages regarding their usage. Quantitative approaches and methods of regulating selection systems are explained, and a number of examples from different forest types are provided, primarily in North America.

The term **selection system** applies to silvicultural programs that are used to maintain all-aged (uneven-aged) stands. An uneven-aged stand contains at least four (rarely three), but usually more, well-defined age classes, where "well-defined" means differing in total height and age, not just in stem diameter. The **selection method** is the component of the system to regenerate such stands. Selection is the only natural regeneration method that is not defined by the focus of the nature and origin of its regeneration. The method is defined by age-class distribution. The selection regeneration method attempts to create an **all-aged** (four or more age classes), or on occasion, a **multi-aged** stand (three age classes) that is **balanced** in age-class distribution (meaning that an equal area is apportioned to each age class within the stand). There are occasions where **unbalanced** selection systems can be applied where age classes are unequally distributed, but in this case, these stands distinctly lack the domination of a regenerating age class. For unbalanced age-class distributions with two to three age classes (multiple-aged), where the youngest regenerating age class dominates, see Chapter 11 dealing with irregular multi-aged systems. Both this chapter and Chapter 11 deal with uneven-aged silviculture but from very different perspectives and approaches to regeneration.

The first timber harvests in most forests typically involve crude, unconscious applications of the selection method, in which only the biggest and best trees are removed. At the other end of the spectrum are some of the most intensive and intricate kinds of silviculture. These may gradually develop from the other, but the original early crude selection cuttings are most commonly replaced by some other method of regeneration.

Selection systems, like intensive plantation systems, have both advocates and critics. In nature, regenerative disturbances that are frequent and small scale have commonly created patchy all-aged stands. These have also been created by partial cutting. There are several kinds of all-aged stands, and there are also conflicting ideas about how to manage them (O'Hara, 1998, 2002). Some foresters have devoted considerable attention to the development of quantitative methods for shaping and molding these stands into self-contained units that will supply a sustained yield of timber. Others have been content simply to develop stands with several relatively balanced age classes and to let yields of timber fluctuate to varying degrees. Sometimes the quantitative methods are used to shape stands into arrangements of diameter classes that some believe to be characteristic of old-growth stands.

The uneven-aged stand is an artificial entity created to help understand what might otherwise be a chaos of little "stands." The question of how large an even-aged patch must be in order to represent an individual stand, depends entirely on the particular context in which the forest is viewed at the moment. Someone concerned about silviculture or logging, for example, may see many little even-aged stands. In contrast, someone concerned about forest administration, wildlife, or watershed management may see these same stands as a homogeneous entity characterized by much internal variation. Whereas the first party would map the little units separately, the second would regard that as a useless complication.

An essentially ecological definition would make the theoretical minimum size of an even-aged stand equal to that of the largest opening that was completely under the microclimatic influence of adjacent mature trees. An opening of this critical size would, at the very center, have the same temperature regime as that which prevailed over a large clearcut area. Such an opening would be about twice as wide as the height of the remaining

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

mature trees. The effects of shade and root competition with adjacent older trees would be significant.

Some observers believe that application of selection systems requires that each stand be made into a self-contained, sustained-yield unit. This condition is one that can be approached but is almost never attained in practice, and even approximations of the condition are difficult to maintain. In fact, single-minded efforts to shape stands into sustained-yield units often produce results that are illogical in the light of other considerations. Nevertheless, the essentially mathematical manipulations involved in these efforts are introduced in this chapter because they have such a powerful appeal to many people, and also because they provide a means of monitoring programs for achieving sustained yield in whole forests. One generalization can be made about quantitative protocols – they are best done with single-species or, on occasion, two-species stands. The more sophisticated the quantitative method, the simpler the stand composition.

There are two common reasons for developing uneven-aged stands that are all-aged with balanced age classes. The first is simply that the stands were inherited in that condition and cannot be replaced with even-aged or two- to three-aged stands without prematurely cutting too many young trees. The second is the existence of management objectives requiring that a stand always have some large trees (Guldin, 1996). These objectives can be numerous, but the three most important ones are: (1) aesthetic considerations, especially in roadside strips and parts of forests that are in public view; (2) achieving sustained yields within smallholdings, by requiring that trees mature in size at short intervals even if they are sporadic; and (3) the mixture of old trees with younger ones for certain species of wildlife, or for other purposes that require diversity of habitats and of the species of plants and animals within them (Guldin, 1996). Other reasons include the difficulty of acquiring natural regeneration on adverse sites, where there may be reason to maintain a permanent source of seed and shelter, and uneven-aged stands may be essential on steep slopes that are either geologically unstable, susceptible to erosion, or subject to avalanches.

The Protocol

The selection method of reproduction involves a series of cuts within a stand with four (rarely three) or more balanced age classes.

1) The **cutting cycle** is the period between each entry into the stand. The mature timber is removed at short intervals with single scattered trees, small groups, or larger patches, in order to open growing space for regeneration.
2) These cuttings are repeated indefinitely and may be at either regular intervals, or whenever the conditions of the stand or other considerations dictate.

In this way, there is no definitive end to the development of the stand (rotation), as in the other regeneration methods, which include the irregular two- or three-age systems, but where the youngest age class (cohort) dominates the successional process over the others. The whole selection process depends on periodically establishing reproduction and on making it free to grow, so that the continuing recruitment of new age classes is achieved. The method consists of one cutting entry at each period, unlike seed-tree and shelterwood methods which often require a sequence of cuttings. In the selection method, the reproduction cutting is typically accomplished by cutting the oldest or largest trees, and, if necessary, enough smaller trees to ensure that enough trees of needed age classes are free to grow. The seed and any protection necessary for natural reproduction come from the trees that remain around the openings.

The regeneration can arise from several sources: new seedlings, advance regeneration, sprouts, or combinations of all of these. In a certain sense, all of the methods of regeneration previously described can be applied in small units of area. Selection systems are thus not defined by the origin and kind of their regeneration, but that the regeneration represents only a part of the stand with at least three (or usually more) other age classes representing the other parts of the stand in a balanced equal amount. Defining that balance is difficult and can be done in a number of ways, as explained later in this chapter (e.g., diameter classes, stand density index, leaf area index). Intermediate cuttings (liberation release treatments, see Chapter 20) may be made among the younger trees at the same time that the older or larger trees are removed. Each immature even-aged aggregation is treated essentially as if it were a stand by itself. Within the entire uneven-aged stand, the periods of regeneration and intermediate cutting might extend through the entire rotation and be indistinguishable from one another.

The Selection Regeneration Method and its Variations

The selection method is often said to favor regeneration only of shade-tolerant species or to be unusable for intolerant ones. This is not true. As has been pointed out before, tree seedlings are small, and their survival is governed by characteristics of microenvironments with dimensions measured in centimeters. For example, shelterwood methods can be modified to regenerate even the most shade-requiring species in even-aged stands.

Likewise, the selection method can accommodate shade-intolerant species in large openings. However, the **single-tree selection method**, which is described below, is associated mainly with shade-tolerant species or stands on sites so dry that crown closure is incomplete. The **group selection** and **patch selection** systems can create much larger canopy openings that, together with lethal site treatments that include scarification, piling and burning, and/or use of herbicides, produce and facilitate the establishment of pioneers.

The semantic matter of defining stand scale for selection systems can be looked at from the viewpoint of someone making administrative maps of forests for determining areas of different age classes. With satellites, aerial photographs, and GPS, it is now more cost efficient to identify "stands" very much smaller than was the case when foresters mapped stands by measuring distances on the ground. It is now much easier to recognize small even-aged stands, and there is less reason to lump them into larger uneven-aged stands. However, stands should be delineated as uneven aged when their uneven age-class distribution is consistently repeated across the area to be delineated, the species composition is consistent across the same area, and the site is sufficiently the same in soil type, hydrology, and fertility. Delineating a stand area with different soil types and species compositions will mean the stand will have diverging areas with different growth rates and successional trajectories. This will require different cutting cycles, opening sizes, and site treatments. By definition, the area should have been subdivided into several stands (see Chapter 3 for stand delineation and site classification). It is suspected that many stands that have been delineated as large and uneven-aged stands actually have varying site and species compositions and should now be re-classified with modern technologies.

Single-Tree Selection System

In the classic form of the selection system, each little even-aged component of the uneven-aged stand occupies a space about equal to that created by the removal of a single mature tree (Fig. 13.1). Theoretically, single mature trees are harvested at short, equal, intervals of time, and each group is thinned artificially or naturally thinned by competition so that only one tree is left at the end of the rotation. The development of even-aged groups of trees in the very small, scattered openings that have been created by the cutting of the mature trees is the main characteristic of single-tree selection. The only reason for making the cuttings at equal intervals of time would be to make the stand into a perfect sustained-yield unit.

The species most likely to be perpetuated in closed-canopy everwet forests, are those that are very tolerant, although the opening left by the removal of a single large tree will, if site conditions are otherwise favorable, allow the establishment of a few seedlings representing early successional stages. However, if the opening is not soon enlarged, the crowns of adjacent older trees will almost

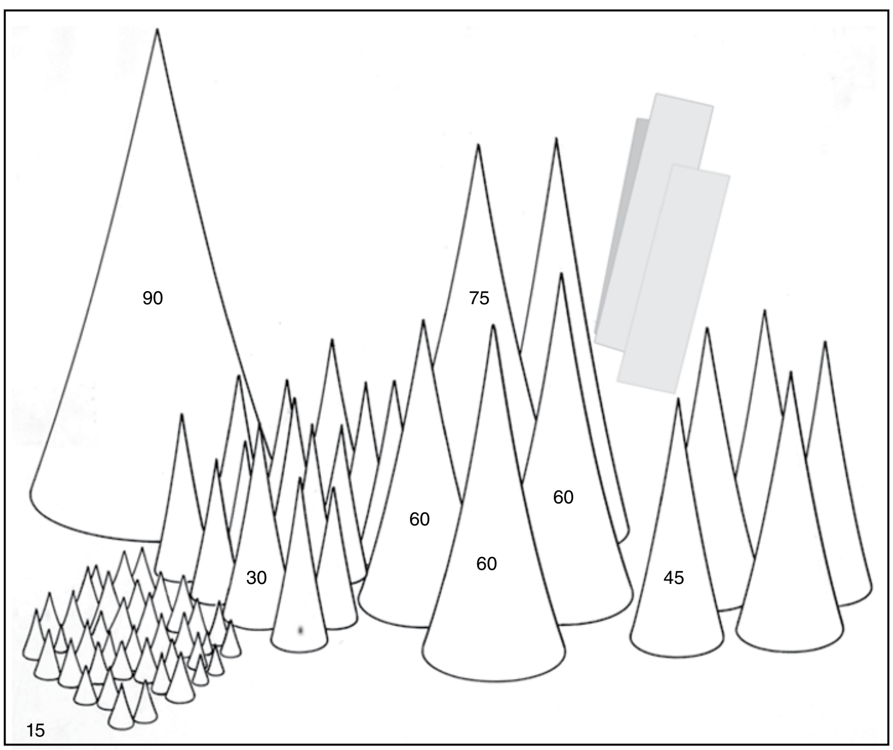

Figure 13.1 Schematic oblique view of a 0.25 acre (0.10 ha) segment of a balanced uneven-aged stand being managed by the single-tree selection system on a 90-year rotation with a 15-year cutting cycle. Each tree is represented by a cone extending to the ground; the numbers indicate the ages. Each age group occupies about 0.40 acre (0.16 ha). The 90-year-old tree is now ready to be replaced by numerous seedlings, while the numbers of trees in the middle-aged groups are appropriately reduced by thinning. *Source:* Yale School of Forestry and Environmental Studies.

certainly widen and overtop all the new regeneration. The difficulty of carrying out light harvests that are often enough to accomplish this, has usually made the single-tree selection system very difficult to conduct. The removal of single trees in thinnings or the choice of trees to harvest on the basis of individual analysis constitutes use of the single-tree selection method only if it results in the establishment of regeneration that is free to grow.

Group or Patch Selection Systems

A much more feasible way of managing uneven-aged stands is the **group selection system** under which the final age-class units consist of two or more mature trees (Fig. 13.2). If the regeneration openings are made larger, it becomes possible to accommodate the ecological requirements of almost any tree species. As previously stated, if the issue is considered from the standpoint of ecological site factors, the maximum width of what are called **groups** could be set at approximately twice the height of the mature trees. With such a classification limit, the same environmental conditions that exist in a huge clearcut area could exist in a group, but only near the center of the opening. Regeneration of some very intolerant species might thus be virtually impossible. A **patch** can be defined as anything larger than two tree heights, and serves the purpose of providing larger and more uniform numbers of pioneers and shade-intolerants into the stand. Group selection provides the opportunity of either encouraging proportionately more species dependent upon advance regeneration by protecting the soil surface and releasing the vegetation at the groundstory, or by encouraging species that require open conditions and the destruction of the groundstory by scarification and/or use of herbicide. **Patch selection systems** include large openings that provide conditions of disturbance that match a small-scale, one-cut shelterwood, or together with scarification and lethal treatments to the groundstory, a small-scale true clearcut for pioneers.

The group selection method has other advantages over single-tree selection cutting (Roach, 1974). The older trees can be harvested more cheaply and with less damage to the residual stand. The trees develop in clearly defined even-aged aggregations, and this characteristic is of substantial advantage in developing good form in many species, especially in hardwoods.

This modification is also more readily applied to stands that have become uneven aged through natural processes, because such stands are more likely to contain even-aged groups of mature trees than a mixture of age classes by single trees. Furthermore, the openings that are created are large enough that the progress of regeneration and the growth of younger age classes are more readily apparent.

It is important to consider the significance of the effects involved in having trees growing on the edges of even-aged aggregations. As the total perimeter of the forest edge becomes greater, the size of the groups becomes smaller (Fig. 13.3). The effects are both beneficial and harmful but vary according to the circumstances. Influences on reproduction are beneficial to the extent that side shade protects young seedlings. However, the competition from the older trees for soil

Figure 13.2 A stand of ponderosa pine in the Fort Valley Experimental Forest, Arizona, managed under the group selection system. The saplings form a group that resulted from one unusually favorable regeneration year. The group that occupies the foreground has been thinned twice to favor trees of superior bole-form such as the ones now remaining; the small cards mark the stumps of medium-sized trees cut 32 years earlier, the large card marks the position of a large member of the group harvested 2 years ago. *Source:* Yale School of Forestry and Environmental Studies.

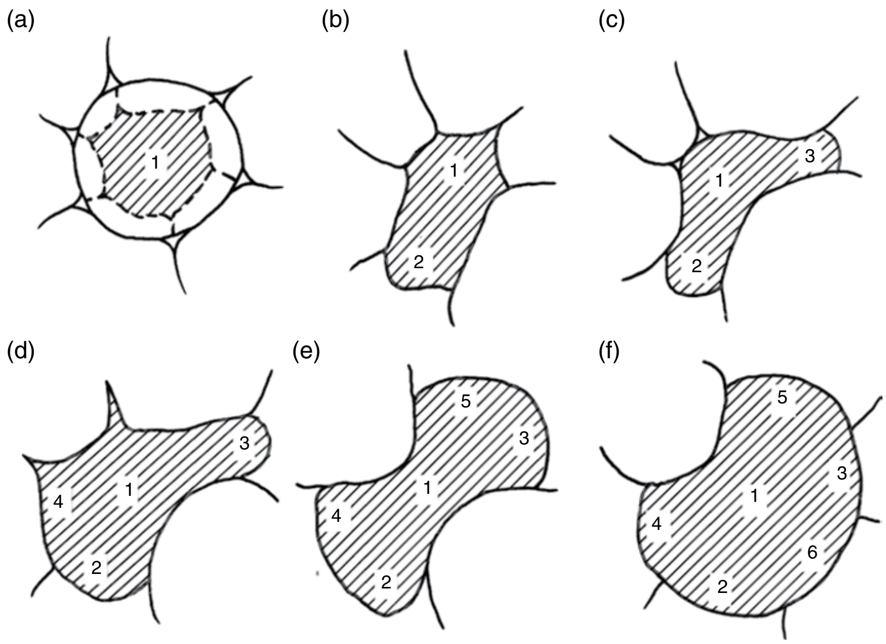

Figure 13.3 The initial contraction and subsequent expansion of area occupied by the trees of one small age group in an uneven-aged stand. **(a)** The circular outline of the area previously covered by a single mature tree that has just been removed; the smaller cross-hatched area 1 is that to which the new age group of seedlings is confined by expansion of the older adjacent trees. Sketches **(b)** to **(f)** show how this group of trees would re-expand as periodic, sequential cutting of areas 2 to 6 successively removed adjacent trees during the remainder of the rotation. *Source:* Yale School of Forestry and Environmental Studies.

moisture can be adverse. The roots of the older trees are capable of spreading out into the newly created openings. They may even do so automatically if they are already attached to the roots of the cut trees through intraspecific root grafts.

The uneven-aged structure of age classes provides an opportunity to release the young trees along each edge, which may occur once during each rotation when the older adjoining groups are harvested. This takes the place of one heavy thinning and is of some advantage when ordinary thinning must be delayed or is not feasible. The effects of this phenomenon on the form of the edge trees vary considerably, depending on the species and circumstances. The development of large branches is forestalled as long as there are larger trees at the side, but the effect is reversed when the larger trees are removed. Distinctly phototropic species such as most of the hardwoods do not fare well, because the stems tend to bend outward toward the light or to become crooked if the terminal shoots are battered by the crowns of taller trees. This is not so true of distinctly geotropic species like conifers, which tend to grow straight under all circumstances.

The simplest kinds of group selection cuts create definite gaps in the forest canopy. If the gaps are large enough, they will, for the reasons described in Chapter 5, provide microenvironmental conditions suitable for the regeneration of species from almost the whole spectrum of local vegetation. The environment of the gap is not uniform, but covers a wide range of microclimates. Both the forester and the ecologist should regard the entire area of small openings as important for various categories of vegetation.

Another ecological attribute of small openings that must be anticipated is their tendency to become pockets of hot air by day and of frost and dew by night. This is because they are not well ventilated by the wind, but are open to the sky, and if large enough, to the sun. At night, plant surfaces cooled by radiational heat loss may not be adequately reheated by contact with warm air that is wafted down from above, so dew or frost may form on the plants. This may cause risk of damage by frost or increase the risk of infection to leaves by fungus spores, such as those of the stem-rusts of conifers. Along with deer browsing, the frost effect has been suggested as a means of controlling unwanted true firs in the regeneration of pine forests in the Sierra Nevada (Gordon, 1970).

The effects of hot-air accumulation in sunlit openings on plants are more obscure. Studies of German spruce forests have shown that the risk of frost is most extreme in openings that are one and a half times the height of the surrounding trees (Geiger, Aron, and Todhunter, 1995). Wider openings are better ventilated and smaller ones more shaded, especially at high latitudes. If these effects are undesirable, one can wholly or partly substitute the effects of more diffuse cover of the kinds associated with,

but not limited to, shelterwood cutting. Partial cover combines some shade with more opportunity for ventilation by the wind, which may be thought of as entering the forest from above, in the degree that canopy openings allow.

Not all the mature trees of a group need be cut at a single time. If desirable because of ecological requirements for reproduction, the need to leave some trees for additional growth or some other consideration, the groups can be reproduced by small-scale applications of the shelterwood and seed-tree methods. There is no necessity that the individual groups in one stand be uniform in size, shape, or arrangement, nor that one age class be represented by a single group. In fact, if proper advantage is taken of the existence of groups of different ages when an irregular uneven-aged stand is placed under management, such regularity is unlikely. A systematic arrangement of individual groups would be convenient but is usually almost impossible to produce.

Strip Selection System

The components of an uneven-aged stand can be created in slowly advancing strips. This arrangement enables the transportation of logs through the next strip to be harvested. There is opportunity to obtain advance reproduction in the side-light adjacent to the most recently cut strip. Similarly, if the progression of cutting is directed toward the equator, regeneration of species that require partial shade may be encouraged. If successive cuttings advance against the direction of the most dangerous winds, the stand gradually becomes streamlined so that the main force of strong winds is diverted up and over the stand. Strip and patch selection cutting have sometimes been effective in creating snowdrifts and thus improving the yield of water from snowmelt (see Chapter 29).

Managing for Balanced All-Aged Stands

The initial idea behind the development of an all-aged stand was simply to more generally apply the concept of sustained yield by managing the forest as a series of little even-aged stands representing all age classes. This gravitated to developing a more perfect age-class distribution driven by a simple mathematical assumption about numbers of trees in relation to diameter class. This more balanced approach is claimed by some foresters to simulate perpetual equilibrium, and keen supporters characterize it as being similar to old-growth stands. However, other foresters demonstrate more flexible quantitative methods of regulation that are not based on assumptions about desirable stand structures and conditions. This is all summarized in the following paragraphs.

The Concept of the Balanced All-Aged Stand

One of the most attractive and idyllic concepts of forestry is that of the theoretical balanced all-aged stand (Davis and Johnson, 1987). It continually yields benefits and regenerates itself steadily, and it is a dynamic system that is always the same and always in equilibrium. The adjective “balanced” means that every age class up to the rotation age is represented by an equal area, so that the stand is a perfect sustained-yield unit. If these conditions are met, it would be possible to annually cut whatever amount of wood the stand produced in a year, and count on doing so indefinitely, if the cutting was done every year, and the schedule was not disrupted by unplanned destructive disturbances.

Even though this condition has a powerful naturalistic appeal, it does not come into existence in nature, but would have to be an essentially artificial creation. Some foresters and ecologists take it as axiomatic that virgin or old-growth forests are in a state of self-maintaining equilibrium. This is a legacy of ecological thoughts relating to climax theory and has since fallen out of favor (Oliver and Larson, 1996). Even if such stands have several cohorts, and biomass production is perfectly balanced by decay and mortality, this does not mean that the stand even approximates a balanced all-aged structure. It would have to regenerate the same amount of forest area each year for about a whole rotation to create the condition exactly. It is a simple encapsulation of good ideas toward which foresters strive by various means but should not expect to achieve perfectly, even in whole forests.

The theoretical all-aged stand would have trees of every age class from 1-year seedlings to old veteran trees of rotation age, but there is not a good way of specifying how many there should be in each age class. The idea that each age class should have foliage covering an equal area has always provided the soundest theoretical basis for sustained-yield management of forests. Unfortunately, it is not possible to regulate a balanced uneven-aged stand directly on this basis, because the necessary measurements of areas of small aggregations of trees and determinations of their ages would be too difficult. Therefore, it is necessary to employ surrogates for foliage area (such as basal area or sapwood area), and resort to modifications and approximations of the idea.

Simplifying Approximations of Balanced All-Aged Stands

The simplest modification has to do with the impracticality of operating in each stand every year. Instead, it is presumed that the stand would be treated periodically, with each period being a **cutting cycle**. The uneven-aged stand would have as many age classes as there were cutting cycles during the rotation. If the result were

a stand with an arrangement of age classes that approximated the all-aged stand, it would be regarded as a balanced, uneven-aged stand. Figure 13.4 is a schematic map of such a stand, and Fig. 13.5 shows how such stands might be combined into a whole forest managed on the basis of some perfect selection system. Confusion and error can be avoided if it is recognized that the best indicator of the rate of future growth of a tree is the amount of foliage that it bears. Just because the diameter of a tree is used as a surrogate for its total leaf area, it does not mean that the diameter of the tree controls the rate of future growth; it is a result of growth and not a cause of it. It also cannot be assumed that every 9-inch shortleaf pine will increase in diameter at the same rate as others of the same diameter in the same stand on the same soil, especially if their positions in the crown canopy are different.

In order to avoid direct determinations of tree ages and the areas occupied by each age class, it is commonly assumed that tree diameter can be taken as the index of age. The distribution of diameters in the stand is used to assess and control the allocation of area of

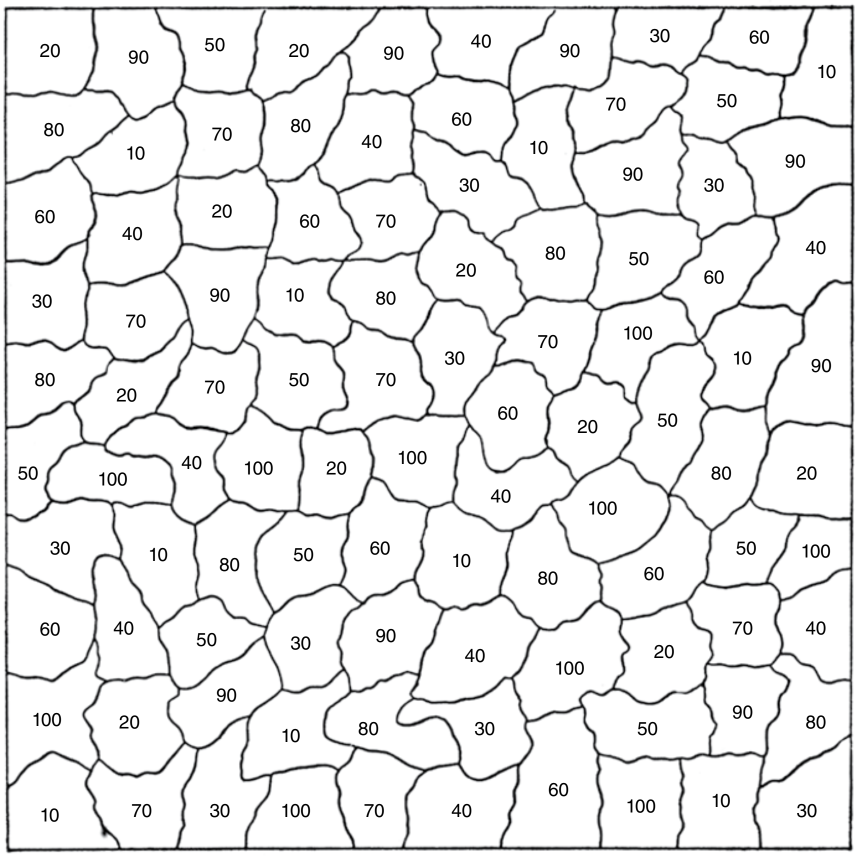

Figure 13.4 A 1 acre (0.4 ha) portion of a fully balanced selection stand managed on a rotation of 100 years under a 10-year cutting-cycle. Ten age classes are represented, each occupying approximately one-tenth of the area. The numbers indicate the ages of the individual groups of trees. *Source:* Yale School of Forestry and Environmental Studies.

Stand 1 contains *age classes*: 1, 11, 21, 31, 41, 51, 61, 71, 81, and 91	*Stand 2* contains *age classes*: 2, 12, 22, 32, 42, 52, 62, 72, 82, and 92	*Stand 3* contains *age classes*: 3, 13, 23, 33, 43, 53, 63, 73, 83, and 93	*Stand 4* contains *age classes*: 4, 14, 24, 34, 44, 54, 64, 74, 84, and 94	*Stand 5* contains *age classes*: 5, 15, 25, 35, 45, 55, 65, 75, 85, and 95
Stand 6 contains *age classes*: 6, 16, 26, 36, 46, 56, 66, 76, 86, and 96	*Stand 7* contains *age classes*: 7, 17, 27, 37, 47, 57, 67, 77, 87, and 97	*Stand 8* contains *age classes*: 8, 18, 28, 38, 48, 58, 68, 78, 88, and 98	*Stand 9* contains *age classes*: 9, 19, 29, 39, 49, 59, 69, 79, 89, and 99	*Stand 10* contains *age classes*: 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100

Figure 13.5 Diagram of a selection forest managed on a rotation of 100 years with a cutting cycle of 10 years. The forest contains 10 stands, one of which is cut each year, thus giving equal annual cuts. Each stand contains 10 age classes, and together the age classes in the 10 stands form a continuous series of ages from 1 to 100 years. *Source:* Yale School of Forestry and Environmental Studies.

growing space to each age class. Total tree height, which has a much higher correlation with effective age, would be better but is more difficult to measure or even to estimate.

Regulation of the Cut by Diameter Distribution for Balanced All-Aged Stands

A series of little stands, each of the same area, conforming to a yield table for pure stands of the same species, is the fundamental basis for defining the mathematics of development of a balanced uneven-aged stand. It is because the yield tables represent observational evidence that predict how pure even-aged aggregations of trees actually develop over time, if they are free to grow. They show the decline in numbers from competition or thinning as well as the increase in the average diameter of each age class with the advancing years. The second column of Table 13.1 shows an appropriate diameter distribution for a pure, unthinned, balanced, uneven-aged stand of loblolly pine, grown on a 40-year rotation and based on a classic yield table of Walter Meyer (1942) that presents diameter distributions for even-aged stands. It is very important to note that trees of a given diameter class will not grow at the predicted rates if their crowns are shaded from above.

The characteristics of the proper diameter distributions are depicted in Fig. 13.6. Because it requires many saplings to cover the space eventually occupied by a single mature tree, the distribution should approximate the smooth, "reverse-J-shaped" curve of Fig. 13.6a. This curve represents the collective total of the diameter distributions of a series of little even-aged, single-species groups of trees, covering equal areas and separated by equal intervals of age, as shown in Fig. 13.6b. The objective is to harvest and replace trees in such patterns that this diameter distribution is the same, either just before or just after each harvesting operation.

Table 13.1 Diameter distributions exemplifying the results of different criteria used to determine these distributions for various kinds of pure uneven-aged stands.

DBH (in)	Yield table 1	BA 128 q = 1.7	BA 80 q = 1.3	BA 80 q = 1.7	BA 60 q = 1.7
	(1)	(2)	(2)	(2)	(2)
6	138	90	35	76	57
8	84	53	27	44	33
10	44	31	21	26	20
12	22	18	16	15	12
14	10	11	12	9	7
16	7	6	10	5	4
18	2	4	7	3	2
20	1	2			
Total	308	215	128	178	135

1) Based on a series of even-aged stands in a yield table for old-field stands of loblolly pine in northern Louisiana, managed on a 40-year rotation: site index of 90 ft, and total basal area of 128 ft^2; based on Myer 1942.
2) Derived entirely from chosen values of *q*, basal areas per acre, and maximum DBH.

Source: Yale School of Forestry and Environmental Studies.

Assuming that the appropriate distribution of age classes has been converted to a diameter distribution within a stand, it is also necessary to consider the small but crucial changes that will be made in the distribution at the time of each cutting (Fig. 13.7). Selection cuttings in such stands involve successive harvests of the largest trees in a stand. A diameter limit (point *x* in Fig. 13.7) is established as an indication of age, with the understanding that trees below this size are in general to be reserved and the trees above this size are to be cut. This diameter limit should be regarded as a flexible guide, rather than as a rigid dividing line. Depending on their silvicultural condition, especially the capacity for further increases in value, a few trees above the limit should be left, and some below the limit should be removed. Trees that are surplus in a given diameter class are usually harvested, except where they are needed to compensate for deficiencies in the next higher or lower classes. Usually, there are surpluses in many diameter classes larger than the smallest that are measured. This can be taken as evidence for deficiencies in seedlings or other small trees within the stand and would need to be corrected by creating larger openings to establish more regeneration.

Thinning may also be conducted simultaneously with the harvest cutting. It must be distinguished from the harvest of the oldest trees, and should take place in clumps of trees that are too young for final harvest cutting. The thinnings should be guided by the estimates of required numbers of trees, shown in a graph (see Fig. 13.7), with surplus trees removed if they are not needed to remedy deficiencies in other diameter classes. The methods of thinning that are used are the same as those employed in even-aged stands. Unlike the final harvest cuttings, the thinnings should not remove the largest trees in the various clumps, unless they are of undesirable form or species. The primary objective of the thinnings should be to anticipate the inevitable reduction of numbers denoted by the steep slope of the J-shaped curve (Fig. 13.7), so as to salvage prospective mortality and allow the remaining trees space for more rapid growth.

The whole program of thinning and stand-density regulation is the key to the crucial question of how rapidly the growing and aging trees flow through the diameter distribution. The process depends on the continual regeneration of stands.

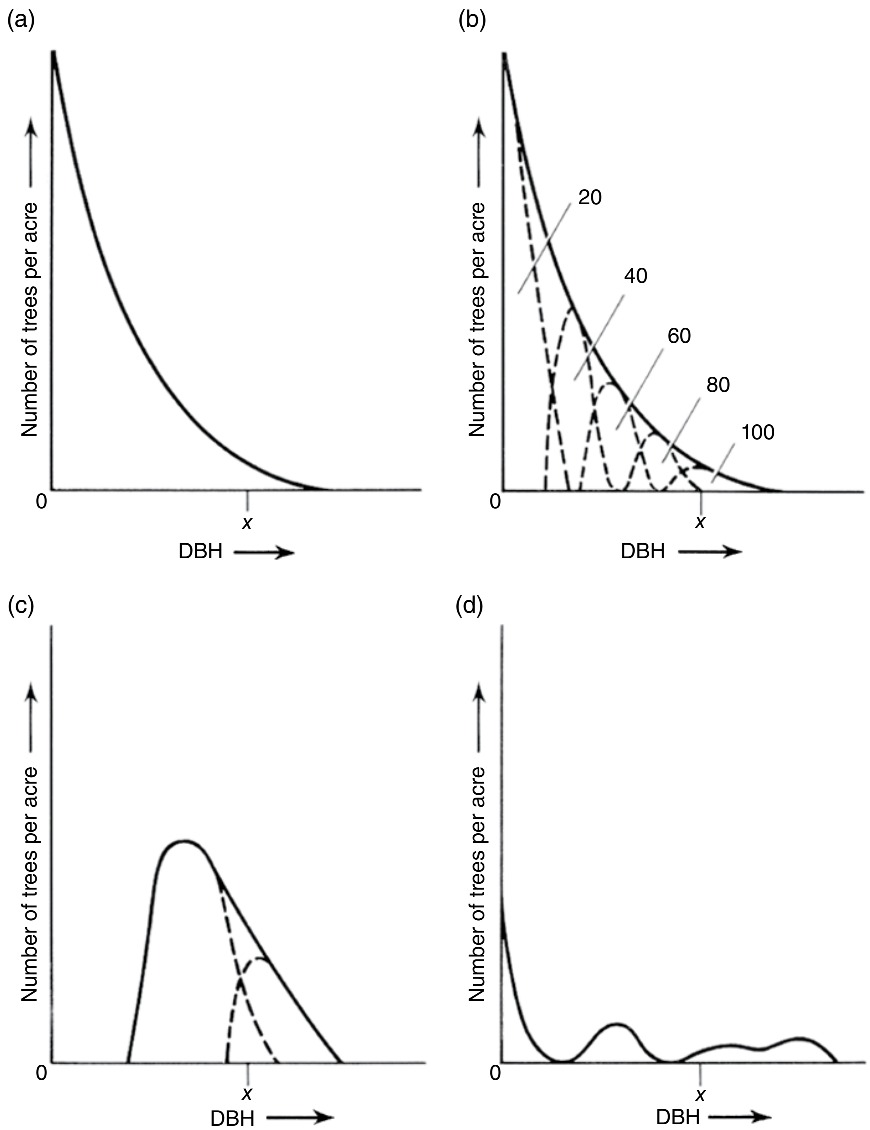

Figure 13.6 Several types of diameter distributions found in uneven-aged stands. **(a)** The distribution curve of an all-aged stand of 1 acre or 1 ha containing sufficient trees in each diameter class to produce an unvarying number of trees of optimum size (of diameter *x* or larger) at rotation age. **(b)** Graph showing how a balanced uneven-aged stand of the same diameter distribution may be composed of five age classes, each occupying an equal area, with a 100-year rotation. **(c)** Graph representing a stand with two closely spaced age classes and no advance reproduction. Uncritically supervised selection cuttings in stands of this kind will produce abnormally high yields of timber until all existing trees reach optimum size; thereafter they will yield nothing until the new growth reaches merchantable size. It is difficult to create the balanced distribution in such stands in one rotation period, especially if the smaller trees do not respond to release after selection cuttings. **(d)** One of the many kinds of irregular uneven-aged distributions that may be found in virgin stands. This one contains four well-distributed age classes, one of which is well beyond optimum age for an economic rotation. This stand could be gradually converted to the balanced form, provided that the intermediate age classes did not deteriorate after partial cutting.
Source: Yale School of Forestry and Environmental Studies.

It has been said that a forester cannot cut more than is grown or grow more than is cut. The stand must be of one species, have the perfect balanced diameter distribution, be cut on the precise schedule just described, and the allowable annual cut under sustained yield is equal to the periodic annual increment in the same unit of measure. It seems logical that one should safely be able "to harvest the annual growth every year," but this is true for a stand or forest only if the stated conditions of perfection have been created and are rigidly maintained. It is prudent to regard the mean annual increment at rotation age for an otherwise similar even-aged stand as the best estimate of the allowable annual cut in a balanced uneven-aged stand. It must also be kept in mind that the appropriate diameter distribution is not the cause of the desired regime of growth and harvest but an indicator and result of the process.

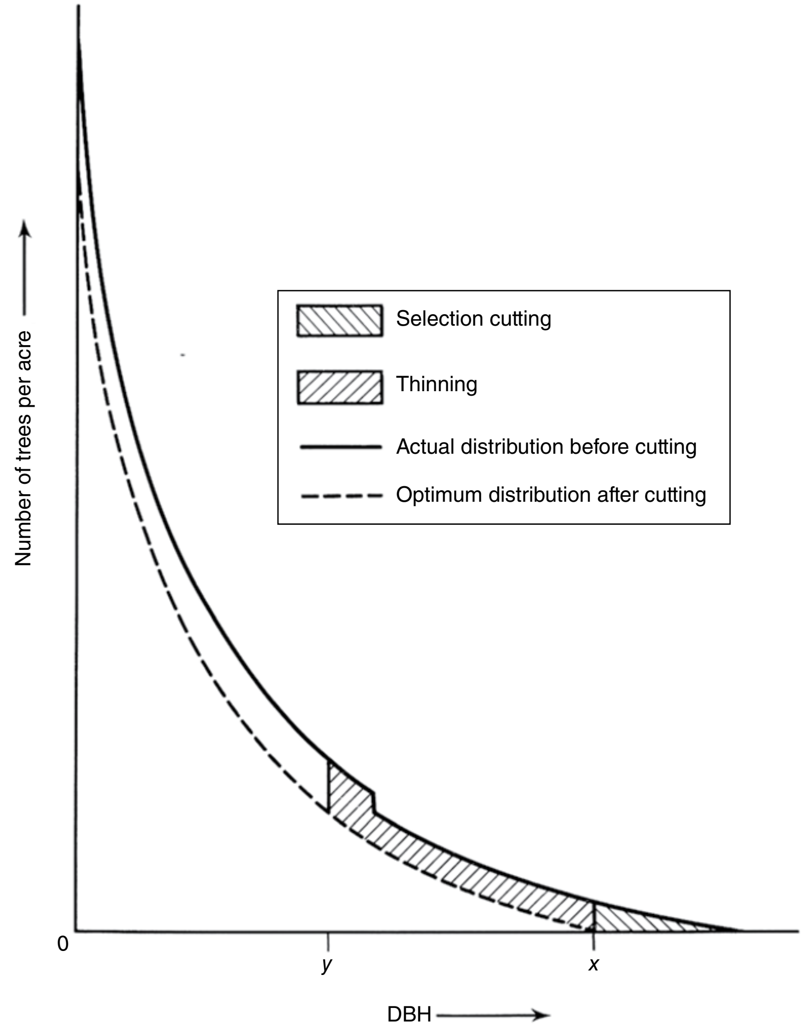

Figure 13.7 Diameter distribution of a balanced uneven-aged stand under intensive management, indicating the number of trees of different diameter classes theoretically removed in a single cutting. All trees larger than diameter (*x*), which has been set as the index of rotation age, are removed. The trees of smaller diameter may also be reduced in number by thinning, provided that they are larger than the tree of lowest diameter (*y*) which can be profitably utilized. Under extensive practice, there would have been no cutting of trees less than diameter (*x*) and most of those represented above as being cut in thinnings that would have been lost through natural suppression. *Source:* Yale School of Forestry and Environmental Studies.

Negative Exponential Distributions of Diameters as Guides for Balanced All-Aged Stands

A different hypothesis about the proper diameter distribution uses a mathematical distribution that has a general resemblance to reverse J-shaped curves, but was not based on ideas about having all of the age classes equally represented. Late in the 19th century, deLiocourt (1898) observed that some very old forests in Europe often had diameter distributions in which the number of trees in each diameter class was some multiple of that of the next larger diameter class. Meyer (1952) noted that, in some very old mixed-species natural stands in North America, this situation prevailed here and that the multiple, termed the *q*-factor, might vary from 1.2 to 2.0. This is also called the BD*q* method, where B equals residual basal area, D equals maximum diameter in the stand, and *q* is the ratio factor. In a stand with a factor of 2.0, each diameter class would have twice as many trees as the next larger class. They assumed (but never verified) that any stand with any value of *q* had arrived at a stable equilibrium and would remain the same perpetually if the effects of periodic harvests or mortality kept returning the diameter distribution to that defined by the same *q*-factor. This assumption of a stable dynamic equilibrium was taken as justification for assuming that the periodic annual increment was the amount that could be harvested under sustained yield forever or at least into some indefinite future (O'Hara, 1996). They also assumed that appropriate numbers of new seedlings would materialize at the right times. Studies by O'Hara (1996) suggest that the *q*-factor is no more reliable than other approaches that create linearly increasing growing space to each older age class. In his study, the use of the *q*-factor for ponderosa pine does not perpetuate a stand structure that represents a size structure typical of pre-settlement fire regimes. These results do not suggest abandoning the use of the *q*-factor, but rather recognizing its faults and caveats if it is to be used (O'Hara and Gersonde, 2004).

Diameter distributions based on *q*-factors fit negative exponential curves. These convert to straight lines if

numbers of trees are converted to logarithms and they are plotted over tree diameters. The appropriate value of *q* defines the slope of the straight line. The allure of this neat mathematical relationship has led many foresters to conclude that *q*-factors define mathematical "laws" governing the growth of trees and stands, although no biological basis has been advanced for the idea (O'Hara 1998, 2002). The relationship does at least define some kinds of reverse-J-shaped curves.

The *q*-factors that are chosen depend on the species and the assumptions that are made about rates of growth and mortality as well as stand basal area and the sizes to which trees are to be grown (Fiedler, 1995). Some choices of the slopes and intercepts of the lines are shown in Fig. 13.8. The slope of each line is the *q*-factor. In customary usage, if the *q*-factor is 1.4, the number of trees in a given 2-inch diameter at breast height (DBH) class is 1.4 times that of the next larger 2-inch class.

Simple direct relationships between basal area, tree numbers, and stem diameter can be used as a guide to construct a stand-structure model (Tubbs and Oberg, 1978). Examples of the effect of some of the choices on diameter distributions with different values of *q*, maximum DBH, and basal area are shown in Table 13.2. For comparison, as previously mentioned, it also shows a diameter distribution for a balanced uneven-aged stand constructed from diameter distributions for known even-aged stands of loblolly pine.

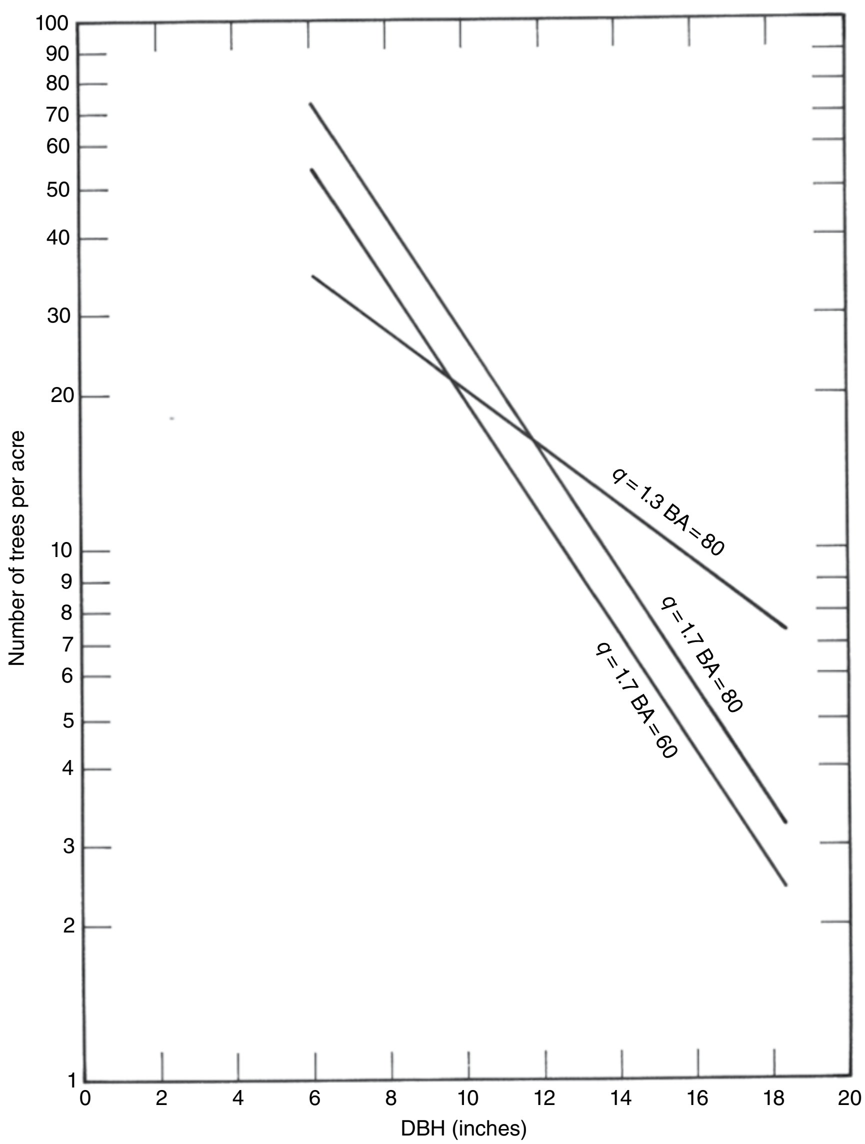

Figure 13.8 Diameter-distribution curves converted to straight lines by plotting logarithms of numbers of trees over arithmetic values of DBH, showing the effects of some changes in values of the *q*-factor and stand basal area (ft^2/acre) that are also shown in Table 13.2. The values of *q* are for 2-inch classes and the stands defined would have no trees larger than the 18-inch class. *Source:* Yale School of Forestry and Environmental Studies.

Table 13.2 Table from Tubbs and Oberg (1978) showing values of a coefficient *K* for determining the number of trees to be grown in uneven-aged stands with diameter distributions of different amounts of basal area per acre and various *q*-factors. Divide the chosen value of the stand basal area by the *K*-value for the desired combination of the *q*-factor and maximum DBH to determine the number of trees in the largest diameter class. To determine the number of trees in each 2-inch class, multiply the number of trees in the next class with larger DBH by the *q*-factor, as has been done for Table 13.1.

Maximum DBH (in)	q-factor						
	1.1	1.2	1.3	1.4	1.5	1.6	1.7
24	18.5	24.8	34.3	48.1	68.0	97.3	139.3
22	14.0	18.2	24.0	32.1	43.4	58.9	80.1
20	10.3	13.0	16.4	21.1	27.2	35.2	45.6
18	7.4	9.0	11.0	13.5	16.7	20.6	25.5

Source: Yale School of Forestry and Environmental Studies.

Possibilities with More Large and Fewer Small Trees for Balanced All-Aged Stands

Diameter distributions defined by the *q*-factor do not fit those distributions deduced from yield tables for pure even-aged stands, as shown in Fig. 13.6b and Table 13.1. The discrepancy lies in the fact that if the relationship specifies the logical numbers of trees in the larger sizes, then there seem to be far too few in the smaller diameter classes. For some, this casts doubt on the validity of using this mathematical relationship in managing stands or forests for sustained yield. Sometimes provision is made to increase the number of small trees by having the *q*-factor high in the small diameter classes, and lower in the middle and upper ranges.

For advocates of *q*-factors, the low numbers of small trees are regarded as evidence of some advantages deemed to be inherent in the uneven-aged arrangements defined by *q*-factors. As a consequence, efforts to deduce appropriate diameter distributions for sustained yield have been diverted into schemes for allocating large amounts of growing space to trees in the middle and large sizes that increase in merchantable volume rapidly (Adams and Ek, 1974; Cochran, 1992). Allocation of space to seedlings, saplings, and other sub-merchantable trees is reduced either deliberately or unwittingly, with or without use of *q*-factors.

The surest way to maximize short-term periodic annual increment of board-foot volume would be by having whole forests with nothing but even-aged stands in the diameter classes of about 13 in (33 cm) where such volume approximately doubles with each 2 in (5 cm) increase in diameter. Unfortunately, if one harvested trees continually from such a forest, the recruitment of new 13 in (33 cm) trees would soon collapse while the large trees were whittled away. Trees have to be small before they can be large.

There are ways consistent with sustained yield for shifting production onto large stems by diminishing the proportion of small ones. Low thinning and crown thinning are the most important ways. If the regeneration units of a selection stand are small, the area that was previously occupied by one or two mature trees is not re-colonized fully by seedlings. Some is taken over by the horizontal expansion of the crowns and roots of adjacent trees. When they are cut in their turn, the regeneration group can take over part of the newly vacated growing space. In this way, as shown in Fig. 13.3, the amount of area used by a given age-class group increases each time an adjacent older group is removed. This effect must have some reality in stands with small age-class groups and, thus, would occupy a large boundary area between groups. However, this effect is negligible if the groups are large.

Another potential source of gaining efficiency lies in the "advance-regeneration effect" described in connection with shelterwood cutting in Chapter 10. If small trees can be grown under large ones, it is not necessary to allocate the space to them that would be required if they needed to grow in the open. As will be described in Chapter 20, this same general effect can be obtained by releasing species of the lower strata of stratified mixtures, including those that are of single cohorts. If this effect was perfectly achieved, it could simply allocate all of the "space" in the regulated diameter distribution to the released trees, and none to those that are too small to release. However, trees of sufficient size to be released would have to be available and they would not grow to this size nearly as fast as they would in an open-grown, even-aged stand. This source of efficiency, to the extent that it exists, is equally attainable with shelterwood cutting.

In stands on very dry sites, there can be another effect that diminishes the required numbers of small trees. In such cases, as in some ponderosa pine stands in the interior of the western US (see Fig. 13.2) (Baumgartner and Lotan, 1988), groups of trees can have root systems that fully occupy the soil, but with crowns that are clearly not close to touching, because the possible amount of foliage is so restricted. This effect is somewhat the same as that involving tree crowns and expanding groups of trees depicted in Fig. 13.3. In these situations, it may not take many small trees to restock an area, and often the effect of root competition seems severe enough to restrict branch size and stem taper without any obvious crown competition (Pearson, 1950). It is also possible that small, slow-growing, but viable trees can grow for long periods

in small openings, if they are kept alive by being root-grafted to their larger neighbors.

Other Approaches to Regulation of Balanced All-Aged Stands for Sustained Yield

The various diameter distributions just discussed are best viewed as ways of relating existing stand structures to those presumed to be desirable. They are useful chiefly in determining which diameter classes are deficient and which are over-represented. They do not dictate whether to work toward the balanced structure, or how fast and for which trees harvesting should be carried out.

Techniques of predicting the development of various alternative kinds of uneven-aged stand structures continue to be developed (O'Hara, 1998). Although the results of such work may be translated into diameter distributions to guide partial cuttings, they are based on some fundamental ecophysiological factors, and not on the idea that the diameter distributions actually control anything.

The Stand Density Index and Leaf Area Allocation Methods

The stand density index allocation method is based on earlier work by O'Hara (1998). Using stand density management diagrams for even-aged forests, relative density values are allocated to diameter classes in an all-aged stand (O'Hara and Gersonde, 2004). The assumption made is that a relative measure of stand density is a better measure than an absolute measure of stand density for allocation of growing space to different diameter classes. Relative density is a weighted unit by size of tree and by logic is therefore independent of the actual size of the tree or the developmental stage of the stand. Comparing diameter distributions using a *q*-factor with those of relative stand density index allocation suggests that the *q*-factor produces an unequal allocation of stand density index and basal area (see explanation in O'Hara, 2014). Developing diameter distributions from the *q*-factor assumes a balanced diameter-class (age-class) distribution when in fact it actually produces unequal amounts of growing space when size-class distribution is based on basal area (Fig. 13.9). To remedy this, Long and Daniel (1990) promote an additive solution:

Stand density index for an even-aged stand is: $N[Dq/25]^{1.6}$

The additive equation for stand density index for a balanced all-aged stand is: $Ni[Di/25]^{1.6}$, where N = number of trees per hectare; Dq is the quadratic mean diameter of the stand in centimeters; Ni is the number of trees in the diameter class; and Di is the midpoint in the ith tree in the diameter class. When smaller diameter classes are excluded, the use of the additive equation may not work (Ducey, 2009).

The soundest of these calculations are based on relationships between amounts of foliage or crown sizes and the accretion of wood (O'Hara, 1995). For this, leaf area index (LAI) has been used as the easiest and most logical measure of total crown surface area per unit area of ground surface (O'Hara and Gersonde, 2004). LAI is directly related to site quality with higher LAIs on better sites than on poorer ones. Assuming maximum LAIs can be calculated for a species or species mixture for a range of site qualities, then comparisons to actual stands and sites can identify the possibilities of improving growing-space efficiencies and re-allocations via canopy strata, species, and/or age classes, rather than the usual proxy of

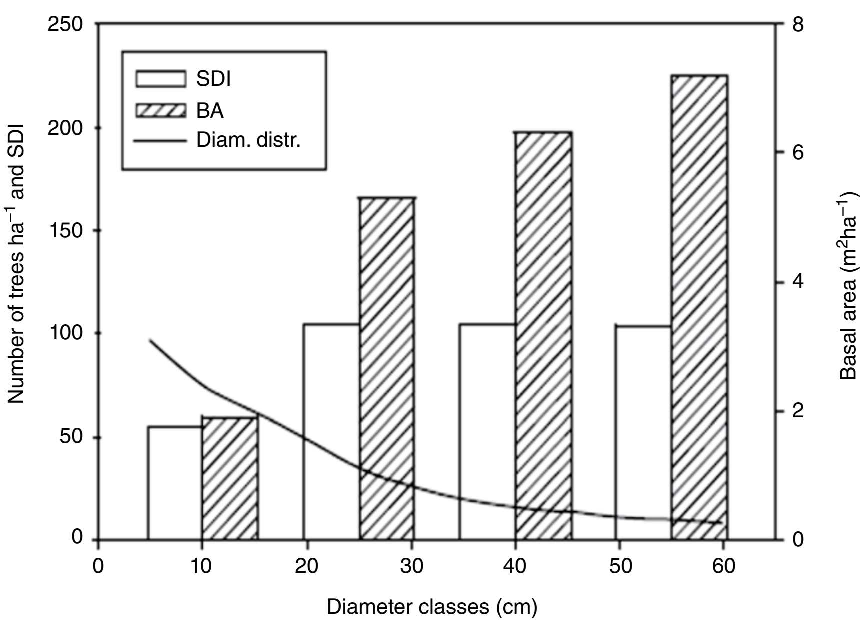

Figure 13.9 Stand density index (SDI), basal area in m^2, and trees per hectare (diameter distribution) for a ponderosa pine stand. SDI is equal for the larger diameter size classes but less for the smallest. However, basal area and SDI are not distributed equally. *Source:* Adapted from O'Hara 2014.

diameter class. To use this approach, the forester needs to identify what amount LAI is desired to be maintained, and how this LAI is to be distributed among the chosen components: canopy strata, species, age class, or a combination (see Box 13.1).

A less rigorous and reasonably successful solution to the problem is to be content with maintaining uneven-aged stands that fluctuate rather widely around the diameter distributions that are tentatively deemed to be appropriate. This process is apparently followed in long-continued management of selection stands in Europe. During the process, changes in distribution and stand volume are monitored, and all reasonable efforts are made to re-adjust them at harvest times. If the larger size classes seem to be over-represented and the periodic annual increment is harvested, it is recognized that the rate of cutting is faster than can be permanently sustained (Burschel and Huss, 1987; Davis and Johnson, 1987). If the periodic annual increment decreases, the diameter distribution can be examined to determine why, and also to deduce what should be done to adjust the situation. If the recruitment of medium-sized trees begins to fail and the growth of the stand declines seriously, steps are taken to start over again with an irregular cohort of trees.

With any approach to balanced uneven-aged management, it is crucial for sustained yield to keep cutting openings in the stands for the recruitment of new regeneration and to set goals in terms of the areas opened, rather than the numbers and sizes of trees cut for the purpose. If the rotation is 100 years and the cutting cycle is 10 years, then the regenerated area should at least approximate a tenth of the total.

Pitfalls to Managing for Balanced All-Aged Stands

Harvest regimes in uneven-aged stands that allocate inadequate space to small trees can sometimes continue for many decades, with rates of cutting greater than can be sustained in the very long run. Forest managers who fall into this trap have sometimes done so by assuming that any diameter distribution that is reverse-J-shaped, or approximates some q-factor in the merchantable size classes, is a balanced uneven-aged stand, and this is usually an important error. The next false premise is that the

Box 13.1 An example of the application of the leaf area allocation method to all-aged stand management using the "multi-aged stocking assessment model" (MASAM).

The example is taken from O'Hara (2014) for a ponderosa pine stand that had a target leaf area index (LAI) of 6 with an allocation distribution among four age classes (cohorts). The information in the model provides target information for the beginning and end of each entry for a cutting cycle, including LAI, basal area, and stand density index (Table 1).

Box 13.1 Table 1 Ponderosa Pine – MASAM.

User-specified variables

LAI = 6

Number of trees per cohort per hectare: cohort 1 = 46; cohort 2 = 61; cohort 3 = 76; cohort 4 = 91; TOTAL = 274

Percent LAI per cohort: cohort 1 = 40; cohort 2 = 30; cohort 3 = 20; cohort 4 = 10; TOTAL = 100

Diagnostic information

	Cohort 1	Cohort 2	Cohort 3	Cohort 4	TOTAL
LAI per cohort at ECC	2.4	1.8	1.2	0.6	6.0
LAI per cohort at BCC	1.4	1.0	0.5		2.8
Leaf area per tree (m^2) at ECC	521	295	178	66	
BA per cohort (m^2/ha) at ECC	12.1	8.3	5.1	2.5	28.1
BA area per cohort (m^2/ha) at BCC	6.3	4.1	2.1		12.5
QMD per cohort at ECC	51.2	37.0	26.0	16.6	
Stand density index at ECC	145.0	114.2	80.8	47.4	387.5
Stand density index at BCC	86.1	64.9	39.6		190.6

LAI = leaf area index; ECC = end of cutting cycle; BCC = beginning of cutting cycle; BA = basal area; QMD = quadratic mean stand diameter (cm).
Source: Adapted from O'Hara, 2014.

conditions have been met under which the allowable annual cut under sustained yield is equal to the periodic annual increment; this harvest rate would be unsustainably high, if too much space were allocated to the larger size classes. The problem is aggravated in situations where whole forests consist of just one age class because all stands arose after a single devastating event. If only trees large enough for sawlogs are counted, a middle-aged stand can sometimes seem to have a reverse-J-shaped diameter-distribution curve. Then, there might be a leap to the conclusion that the whole forest is, and should be, composed of all-aged stands in which the allowable annual cut is equal to the current annual increment. This expression of stand growth rate is unsustainably high in stands that are not yet at the rotation of maximum mean annual increment. If this situation is allowed to continue too long and new age classes are not recruited, some future generation will run out of trees to harvest, and it may take at least one human generation of diminished timber harvests to correct the situation.

Creation of Balanced All-Aged Stands

Theoretically, an absolutely even-aged stand can be replaced by a balanced uneven-aged stand during the period of one rotation (Nyland, 2016). If the new stand is to have five age classes with a rotation of 100 years, all that is necessary is to conduct cuttings that lead to the establishment of reproduction on 20% of the area at 20-year intervals. Thus, some parts of the stand must be cut before or after the age of economic maturity. The disadvantages of such awkward timing of the harvests can sometimes be mitigated if any parts of the stand that mature early are replaced first, and those that continue to increase in value longest are cut last. The conversion will be successful only to the extent that the cuttings are appropriately timed and heavy enough to lead to the establishment of the age classes and species of reproduction desired. It is usually a fallacy to pretend that the large trees of essentially even-aged stands are older than the small ones, and to attempt to make the conversion by successive cuttings of dominants (Nyland, 2016).

The creation of balanced uneven-aged stands can be carried out more rapidly and easily in stands that already contain several age classes. Ordinarily, these will be in irregular distribution, having resulted from a history of high-grading or patchy natural disturbances. It will usually be necessary to make the sacrifice that is needed, by cutting some trees earlier or later than might otherwise be desirable. Sometimes small, relatively old trees of the lower crown classes can be substituted for non-existent dominants of the same size and younger age, thus inventing “age” classes that might otherwise take decades to grow from seedlings. This shortcut is useful to the extent that the trees involved can withstand exposure and return to full vigor. However, it would be a mistake to indulge in this procedure to the exclusion of the creation of the new age classes of seedlings that must be continually recruited, and made free to grow, if the balanced distribution of age classes is to be completely developed. The age-class distribution of a stand is likely to be re-adjusted with least sacrifice of other objectives if the changes are made very gradually. Several rotations might be required to transform essentially even-aged stands to the balanced uneven-aged form.

The degree of precision of the regulation of the cut that is necessary for maintaining or creating any real approximation of a balanced, uneven-aged stand, cannot be achieved without making an inventory of the stand before marking it for cutting. Usually, this involves determining the distribution of diameter classes by basal area or numbers of trees per acre (hectare). The prospective cut is then allocated among the various diameter classes on the basis of a comparison between the actual distribution, and what is assumed to represent the balanced condition. Leak and Gottsacker (1985) described an expeditious way of guiding the marking by (1) using prism-point sample plots to assess stand conditions, and (2) having only three broad classes of tree diameter.

Managing for Unbalanced All-Aged Stands

There are many valid reasons other than sustained yield for maintaining uneven-aged stands with four or more age classes. These other objectives can be achieved without the balanced arrangement. For example, applying the concept of financial maturity in an uneven-aged stand in order to extract optimum value from the growing stock is very likely to continue to promote the development of the condition of an existing unbalanced, uneven-aged stand. So it is logical to continue to use the selection system for uneven-aged attributes and economic conditions, just as it would be to employ the shelterwood system under different economic circumstances in an even-aged stand. Switching between uneven-aged and even-aged, needs careful analysis, and often does not make financial sense but can make strong ecological sense. This is because the sequences of cutting necessary for true sustained yield and those guided by the concept of financial maturity are usually compatible only in uneven-aged stands that are already balanced and composed of good trees. If the diameter distribution is unbalanced, it can be brought into balance only by cutting some trees long before or long after they are financially mature.

Most reasons that exist for having uneven-aged stands and using the selection system are not concerned with manipulating the growing stock of stands, in keeping

with the concepts of either sustained yield or financial maturity. Rather, they may have to do with nothing more than the pre-existence of the uneven-aged condition. The purposes may be, entirely or partly, matters of beauty, wildlife habitat, seedling ecology, or protection of stand, soil, or site. Such objectives may require uneven-aged stands, but not balanced ones. In fact, the warping of patterns of harvest removals to fit some pre-ordained diameter distribution commonly interferes with fulfilling many other logical purposes.

If an uneven-aged stand is to be allowed to remain unbalanced and not be refitted to some diameter distribution, it is not necessary to take the costly step of determining the diameter distribution before the stand is marked for partial cutting. The distribution of age and diameter classes can be allowed to fluctuate almost at random, except to the extent that the cutting or reserving of particular classes must be adjusted to balance the books of sustained yield for the whole forest. In this kind of management, the allowable cut and its approximate distribution among diameter classes are determined for the entire forest, and then harvests are made in various stands on the basis of other considerations, silvicultural and otherwise, until the scheduled volume and kinds of trees are removed.

Theoretically, the true reproduction cuttings of the selection system involve removing the oldest and largest trees, with some pre-determined diameter limit being taken as a definition of the smallest trees that are old enough for cutting. However, this should be only a first approximation of the characteristics of trees selected for harvest. Trees above the limit may be left because they are increasing in value with unusual rapidity, or for reasons such as their capacity to provide seed and protection for reproduction. The trees designated for cutting, even though they are below the limit, are: (1) those that increase in value too slowly because of low quality or poor growth; (2) those that interfere with logging or the growth of better trees; or (3) those that are likely to be lost before the next cutting. In other words, the trees to be removed are chosen based on the same principles that are followed in thinning.

The guidance of such complicated timber marking is sometimes facilitated by tree classifications (e.g., Kraft Crown Classification). This is especially true if the various age groups are small, because the standard Kraft Crown Classification (Kraft, 1884) is most useful in rather large, pure, single-canopied, even-aged aggregations (see Fig. 4.4). In other kinds of stands, the Kraft classification must be supplemented by other information, although the position in the crown canopy is always important. The other characteristics important in deciding whether trees should be cut or left are (1) age or size, (2) quality, and (3) vigor. Tree vigor is usually assessed by observations of the foliage, which is the most crucial productive machinery of the tree. The condition of the foliage can be categorized in terms of its amount, color, density, and leaf size. If attention is given to the quality of the foliage, the live crown ratio is a very useful index of tree vigor.

The extensive kinds of unbalanced all-aged stands are treated by selection cutting, often with a diameter limit. The diameter limits can be set with varying degrees of sophistication. In mixed stands, for example, it may be beneficial to set a low limit for species of little future promise, but higher limits for the more valuable species. These applications may be used indefinitely, or may be used as only temporary measures until conditions become more favorable. The cutting cycles are usually long, and there is seldom anything similar to intermediate cutting; there is little control over stand density or species composition.

Economic Selection Methods and "Selective Cutting"

In situations where landowners have no interest beyond liquidation of existing merchantable timber, foresters have used one important principle of the selection method as a way of encouraging the retention of growing stock. There is always a limiting diameter below which trees cannot be profitably utilized for a given purpose, because the handling costs exceed the sale value of the small material that is produced. The tree that can be harvested with neither profit nor loss is referred to as the **marginal tree** of the stand or forest in which it occurs. A cutting that removes all trees that can be utilized without financial loss is called a **zero-margin selective cutting**. If a landowner can be induced to recognize the existence of the marginal tree, it becomes clearly desirable to leave smaller trees in the forest. If the presently unmerchantable trees are sufficiently large and numerous to provide the basis for another harvest in the near future, there is an additional incentive to protect the smaller trees and to shift away from a policy of short-term liquidation.

This approach is effective in getting the practice of forestry established, but is not an appropriate basis for long-term sustainability. In fact, as economic factors become more favorable, the size of the marginal tree often drops to the point where virtually every tree in a stand can be utilized at a profit. Under these conditions, zero-margin selective cutting may verge on what would look like a clearcut with no site treatment. This kind of cutting has often been defined loosely as "commercial clearcutting". There are variants to this approach where different species have different degrees of zero margin, or where some species have no economic value at all. In mixed-species stands of moist temperate and tropical realms, this approach was, and still is, a very dominant practice leading to the liquidation of merchantable species and the dominance of non-merchantable species.

The primary drawback of basing the selection method on the concept of the marginal tree is that the potential value of different trees for future growth is not taken into account. Although a tree may be logged profitably at a given time, it often can be harvested at an even greater profit at some later date. Once a landowner is committed to retaining small trees for growing stock, it becomes desirable to know which trees are best reserved to the next cutting cycle. This can be done by using the concept of financial maturity to detect those trees that will earn an attractive rate of compound interest on their own present value, if left to grow. This procedure usually results in setting a guiding diameter limit that is substantially higher than the one that would apply to zero-margin cutting. If the total return to be obtained during another cutting cycle is high enough, the practicability of continuing operations at least to the end of that cycle is demonstrated through financial maturity analysis. This line of financial logic is often sufficient to guide forest practice up from "mere tree mining," to a level of extensive practice likely to ensure some continuity of management.

If practice can be intensified still further to achieve optimum production and sustained yield, the suitability of the selection method should be re-examined. From 1930 to 1950, many authorities regarded extensive applications of the selection method, described as "selective cutting," as the panacea of American forest management. The times were peculiarly appropriate for such proposals. The development of trucks and tractors suitable for use in logging big timber had begun to displace railroad logging, thus making partial cutting possible in old growth. The lumber markets of that period were so badly depressed that only the biggest and best trees could be harvested profitably. Most owners were not willing to make significant investment in regeneration. In some cases, foresters were not sure that they knew how to regenerate the stands if they had funds to do so. Partial cuttings provided a means of postponing regeneration until the necessary funds and knowledge were available. Selective cutting played a highly important role in demonstrating that partial cutting was feasible and that residual stands of usable timber could be profitably left for future harvests.

Unfortunately, selective cutting also proved to be a tool that could be used for evil as well as good (Isaac, 1956). Much of it was simply high-grading that did not result in the maintenance of the uneven-aged stand, the establishment of desirable reproduction, or the preservation of the residual trees. Selective cutting, and indeed much of the idea of uneven-aged stands in general, fell out of fashion during the 1950s, when many owners overcame their reluctance to invest in regeneration, and various forms of even-aged silviculture were found to be more effective. As usual, the pendulum swung too far. It has not stopped swinging.

Application of the Selection Method of Regeneration

Species and forest types suited to selection systems can be defined by their degree of shade tolerance and dominance. Shade-tolerant species are more suited to a selection system, compared to their more shade-intolerant competitors. This is particularly true for the single-tree selection method. To include more shade-intolerant species, group selection or patch selection approaches are necessary (Table 13.3). Also, single-species forest types are more conducive to selection systems because there are no other species associates that can compete for resources, and the book keeping to develop and ensure a balanced all-aged stand is logistically and economically more feasible. Some examples of species and forest types where different variants of the selection method of regeneration can be practiced, are listed as: coastal forests of the Pacific Northwest; forests of the Intermountain Region; southern pine; oak–hardwood; spruce–fir and northern hardwood; and tropical rainforests.

Coastal Forests of the Pacific Northwest

The tree species and forest types most conducive to single-tree selection systems of the west coast are also the most shade tolerant. This includes the redwoods along the coast range of California and the firs (subalpine, red, and white firs), spruces (Engelmann spruce), and mountain hemlocks of the Cascade and Sierra Nevada Mountains (Franklin, 1977). Redwoods can be regenerated primarily by group selection with 1–2.5 acre (0.4–1.0 ha) openings at cutting-cycles of 5–15 years (Thornburgh *et al.*, 2000). Smaller openings tend to promote high seedling mortality from pathogens such as damping-off fungi.

In addition, forest types that include shade-intolerants, such as ponderosa pine and lodgepole pine (see section on Intermountain and southwest areas for details) can also be regenerated by selection systems because the harsh conditions of climate and soil precludes shade-tolerant species. For some forest types, such as western hemlock–Sitka spruce, the selection method is not used because the trees are prone to windthrow from shallow lateral rooting and waterlogged soils. Practicing single-tree selection in Douglas-fir–western hemlock or Douglas-fir–redwood are good examples of where the composition of the forest will shift almost entirely to only the shade-tolerant hemlock and redwood, respectively. The Douglas-fir–western hemlock type is also very susceptible to windthrow. In these circumstances, it is better to move to a more even-aged approach with irregular seed-tree systems (see Chapters 9, 11) that promote the inclusion of the shade-intolerant Douglas-fir. However, even Douglas-fir can be regenerated by group

Table 13.3 Some examples of species and forest types suited to selection systems in North America. Almost all species can be managed through selection systems, but it is the nature of the site treatments and the size of the opening that define biological success while the strength of the market or social value that people desire that defines the socio-economic feasibility.

Coastal forests of the Pacific Northwest

Species mixture	Opening size	Site treatment
Douglas-fir–western hemlock	Group or patch selection	Crush and chop slash, and then scarify patches; may be necessary to follow up with herbicide application to control hardwood competition
Redwood–Douglas-fir	Group selection	As above
Mixed conifers of the Sierra Nevada	Group selection	As above

Conifer forests of the Intermountain and Southwest Region

Species mixture	Opening size	Site treatment
Engelmann spruce–subalpine fir	Group selection	Some scarification may be needed
Ponderosa pine	Single-tree or group selection	Some scarification and prescribed burning may be necessary
Lodgepole pine	Patch selection	Distribute slash and prescribe burn

Southern pine forests

Species mixture	Opening size	Site treatment
Longleaf pine	Group selection	Prescribed burning of slash
Loblolly–shortleaf pine	Single-tree or group selection	Vigorous control of hardwoods necessary by periodic use of herbicide and use of release cleanings
	Patch selection	A more feasible alternative to single-tree selection with prescribed burning of slash and use of herbicide

Oak–hardwood forests

Species mixture	Opening size	Site treatment
Oak–hardwood	On mesic sites, openings need to be patch-sized to allow oak to compete with shade-tolerant maples	Scarification or burning may be needed, or protect advance regeneration and ensure its presence before opening canopy
	On dry sites, single-tree or group selection can be practiced because shade-tolerant competitors are absent	None; protect ground surface; ensure oak advance regeneration is present before opening canopy
Bottomland oak	Single-tree selection with thinning	Release work needs to be continually done to keep the stand open enough to allow the oak to move upwards
	Patch selection	Timing the patch opening to after a mast year is critical for best establishment; release work will be necessary to remove older shade-tolerant trees

Maritime boreal forest

Species mixture	Opening size	Site treatment
Balsam fir–red spruce–white pine	Single-tree selection favors spruce and fir	Only need is to protect the ground and advance regeneration
	Group selection favors white pine and red maple	
Black spruce–northern white-cedar	Single-tree selection	A reliance on layering; site protection needed; best operations in winter

Source: Mark S. Ashton.

selection where it is mono-dominant on dry interior sites on the eastern side of the Cascades.

On the wetter western side of the Cascades, Douglas-fir has traditionally been managed on private lands through single-species plantations that are established with intensive site preparation. However, with some careful treatment, Miller and Emmingham (2001) have shown that a single-tree selection can be used for private landowners, using a relatively intensive cutting cycle (every 5–10 years), provided that overstory stocking is low (one-half of an even-aged stand) to promote Douglas-fir over its more shade-tolerant competitors (grand fir, western hemlock).

The mixed-species conifer stands (ponderosa pine, Jeffrey pine, western white pine, sugar pine, and white fir) of the Sierras can be managed by group selection and strip selection, where gaps are sufficiently large enough (1–2 tree heights) to encourage the shade-intolerants over the fir (York, Battles, and Heald, 2003).

Selection Methods of the Intermountain and Southwest Region of the United States

Pure uneven-aged stands are most commonly found and easiest to maintain on sites that have such seasonal deficiencies of available water that natural monocultures are favored. These deficiencies may result simply from drought found at low elevations, physiological dryness caused by low soil temperature, or the accumulation of poorly aerated water found at high elevations. On such sites, conditions are only sporadically conducive to regeneration, so it helps to retain trees that can produce seeds whenever circumstances allow. In such cases, tree growth is usually too slow to justify the high cost of planting, so only natural regeneration is used. Another reason for uneven-aged stands in these circumstances is the desire to maintain the survival of nearly every seedling. If these come in sparsely and infrequently, the inevitable result is likely to be an uneven-aged stand.

The evolution of the selection approach is described well by Cochran (1992), for the dry ponderosa pine forests of the interior of the western US. Many stands are composed of small even-aged groups of trees that have arisen when trees were killed by bark beetles, lightning, dwarf mistletoe, or the irregular lethal effects of fires. In these kinds of stands, group selection management has long been common (Boyden, Binkley, and Shepperd, 2005) (Fig. 13.10a). The species has a broad geographical range, and the patterns of seasonal dryness to which it is exposed differ considerably, as does its management. The only part of the range in which regeneration is easily secured is a region of summer rainfall that lies east of the Rocky Mountains, and includes the Black Hills of South Dakota. Most of the stands in those localities are even aged, and are typically managed with shelterwoods because of the relative ease of regeneration (see Chapter 10).

The widest part of the ponderosa pine range lies between the Rocky Mountains and the mountain chain formed by the Cascades and the Sierra Nevada to the west. At the north there is a long, dry summer but with just enough extension of the winter rains into the spring that it is only moderately difficult to obtain regeneration. The group-tree and single-tree selection methods or the seed-tree method is used, but has evolved with changes in both timber markets and non-market social values. Before the 1940s, the old-growth forest was still impacted by *Dendroctonus* bark beetles, and the limitations imposed by railroad logging. It was anticipated that this cumbersome mode of log transportation would dictate a long cutting cycle of about 30 years. Only fine old trees more than about 20 in (51 cm) DBH were worth cutting. The Keen Tree Classification was devised as a basis for predicting the survival prospects of various categories of trees for the long cutting cycles that were envisioned. It was used as the basis of financial maturity analysis (see Chapter 30), which also guided the choice of trees for harvest or retention. In fact, this approach, termed the **maturity selection system** (Munger, 1941), was perhaps the most successful selective logging scheme of the era, because it closely fit the existing developmental processes in truly uneven-aged stands.

With the advent of tractor logging, and much more favorable markets, it became possible to shorten the cutting cycles and produce thinning effects by cutting in a broader range of diameter classes. Problems with the bark beetles subsided as large, old, susceptible trees were eliminated. It has gradually become more customary to prescribe treatments for individual stands on the basis of their prevailing condition, rather than following some standard system. At one time, the term **unit area control** (Hallin, 1959) was used to denote this shift in emphasis. The "unit" was any homogeneous part of a large, heterogeneous stand, but it gradually came to be recognized as a small, separate stand in its own right. As problems such as dwarf mistletoe and the need for site preparation to deal with brush competition got increased attention, even-aged systems became more prominent among the alternatives, including planted stands. Concern about the invasion of tolerant conifers from fire suppression, and increases in the amount of forest fire fuel, have also made it desirable to institute thinning and prescribed burning beneath the stands.

Further south in Arizona and New Mexico, severe drought in spring makes regeneration of the forest a rare event. These areas have summer showers and thunderstorms, but they do not occur in time to produce seedlings that will germinate early enough to harden before frost. In 1919, the combination of an abundant seed crop, the existence of much vacant growing space from

Figure 13.10 **(a)** Group selection for mixed conifers in the Sierra Nevada at the Blodgett Experimental Forest, University of California Berkeley. *Source:* Mark S. Ashton. **(b)** An uneven-aged stand of Durango pine on a soil in northern Mexico where it is moist during part of the summer, but very dry throughout the rest of the year. *Source:* Yale School of Forestry and Environmental Studies. **(c)** Patch selection of 10-year-old lodgepole pine in interior British Columbia, Canada. Patches have to be sufficiently large to ensure regeneration of the shade-intolerant pine. The slash was distributed across the patch at the time of cutting and then burned. *Source:* Mark S. Ashton.

previous fires or heavy grazing, and unusual spring rains brought abundant pine regeneration to northern Arizona (Covington *et al.*, 1997). The 1919 age class filled so much growing space that, for some decades, it was logical to turn to other silvicultural management problems. Since bark beetles were not a major problem, the selection cutting could be aimed at developing trees with good bole-form and natural pruning. A program for doing this, called **improvement selection cutting** (see Fig. 13.2), and many other aspects of ponderosa pine silviculture were described by Pearson (1950). He worked with pines with small crowns and branches that responded to release, and turned them into fine trees.

In most of the ponderosa pine types, the selection system has been used to take advantage of rare regeneration episodes. In a different general case, the selection system is often used to take advantage of easy regeneration, coupled with weak competition from undesirable species. Such circumstances exist on specific sites in many regions where there is good rainfall at the season of seedling establishment, but such poor moisture supply at other times that only drought-tolerant species can endure. Various species of pines have this adaptation. Under just the right soil-moisture regime, the regeneration phase of silviculture may require little more. This situation can develop on soils of deep sand, such as glacial outwash or old coastal beach deposits in humid climates. If the stands are already uneven aged, there is little reason to convert them to the even-aged condition. The dry soils usually make the logging easy and reduce problems with undesirable vegetation. Any large vacancies created in the growing space by cutting, usually fill up promptly and almost automatically with dense regeneration. Ordinarily, the main problem is that the natural regeneration is much too dense and precommercial thinning may be required. Such sites are more common in the western interior; examples are the kinds of ponderosa pine sites where regeneration is easy but brush competition is not serious. Another important case is the mountains of northern Mexico, which have some uneven-aged, easily regenerated forests of *Pinus durangensis* and *P. arizonica* in a summer–wet, winter–dry climate (Fig. 13.10b).

Whether this dry-site regeneration is difficult or easy, it is often associated with root competition. The supply of available water is often small enough that the invisible root systems can be fully closed but unable to support a closed canopy of foliage. The stands easily develop persistent gaps that appear to be unstocked, but are actually being fully utilized by the roots of adjoining trees. If root grafting is well developed, as it often is with pines, partial cuttings may merely donate the use of living roots of the cut trees to the remaining ones. This is good for the remaining trees but can defeat efforts to create real soil vacancies for regeneration. The application of herbicide to the cut stumps and/or deep soil scarification may be the only alternatives to open up growing space when a lot of grafting is present.

Pure lodgepole pine stands can also be regenerated with all-aged stand structures, but the opening sizes must be a mosaic of large patches that, to some degree, mimic true clearcuts (Fig. 13.10c). The size and coarseness of these patches should imitate the type, frequency, and intensity of disturbance recorded within the region, namely cycles of drought, bark beetle outbreaks, and fire (Stuart, Agee, and Gara, 1989). On the other extreme, the Engelmann spruce–subalpine fir of high elevation in the Rocky Mountains can be regenerated with a hybrid single-tree/group selection, creating the disturbance regimes of the forest type that eventually must be regenerated by an irregular seed-tree/true clearcut method that includes individual and group reserves (Alexander and Ernster, 1977). The natural fire-return intervals and insect outbreaks are 200–400 years and are generally lethal to sublethal crown fires of mixed severity that are not in equilibrium (Hessburg, Salter, and James, 2007). Between these long intervals of time, the stands originate as diverse mixtures of spruce, fir, pine, and aspen, but then develop into irregularly uneven-aged patches of single-species, late-successional spruce because of windthrow, ice storms, and avalanche events (DeRose and Long, 2007).

Southern Pine Forests

There is a narrow range of site and disturbance conditions that make it possible for pine to continuously exist as a late-successional forest type in the wet temperate regions of eastern North America. These sites occur in the eastern and southern parts of the United States only on deep, sandy soils, which are often among the poorer soils for tree growth. They are the easiest places to grow longleaf pine, slash pine, pitch pine, eastern white pine, and other pines, because hardwood competition is weak.

Deep sands in humid climates can present an additional peculiar phenomenon. The problems with moisture deficiency may be mostly near the surface. Although trees may grow slowly at first, they can grow at accelerating rates for long periods, as their roots become increasingly extensive and tap moisture at deeper horizons. What may seem to be poor sites initially, become much "better" as trees grow their roots deeper. If the trees in crowded groups differ enough in height, then the larger trees will continue to grow ahead, even without the benefit of thinning because their root systems become deeper.

The most obvious forest type that can be regenerated by the selection method is the longleaf pine–wiregrass ecosystems that grow in nutrient-poor, sandy soils (e.g., the sandhills region of South Carolina and Georgia). The

larger gaps of group selection is the preferred method, primarily because falling needle litter and hotter fires beneath the canopy or adjacent to small gaps, can kill young seedlings (Brockway and Outcalt, 1998). In addition, parent tree roots compete with seedling roots for soil moisture and nutrients at least 40–53 ft (12–16 m) beyond the canopy edge. Thus, gap openings should be at least 40 ft (12 m) in diameter in order to minimize competition with adults (Brockway and Outcalt, 1998).

The Stoddard–Neel approach (see Jack, Neel, and Mitchell, 2006; Moser, 2006; Neel, Sutter, and Way, 2010) to managing the longleaf pine–wiregrass system has primarily evolved for the purpose of creating wildlife habitat for quail. Prescribed broadcast burning is used frequently (nearly every year) to maintain very open understories that control hardwoods, and provide suitable sites for quail, longleaf regeneration establishment, and herbaceous and forb diversity. Timber is not the primary driving value in this system but is chiefly used to pay the bills for the other benefits. The method of harvesting is a variation of the single-tree approach with each tree evaluated individually to be kept or removed. The marking is very opportunistic; if regeneration is present, the forester may create a small gap above it by taking out a tree; if a gap is already present and advance regeneration has been released, the forester might increase the size of the gap. With this process, the marking is variable and the stands vary in the amount cut from area to area and in cutting-cycle intervals. Thus, volumes harvested are quite variable at each cutting.

If enough effort is dedicated to controlling unwanted species, it is possible to grow pure uneven-aged stands of many pine species on any kind of site. Another well-documented case history (Reynolds, Baker, and Ku, 1984) involved stands started in southern Arkansas with loblolly and shortleaf pine. These species characteristically grow together in even-aged stands, so their successful culture in uneven-aged stands is proof of the versatility of the method. The basic objective of the procedure is to develop good sawtimber growing stock as swiftly as possible, from the remnants of high-graded, even-aged stands. New stands can be created from many small- or medium-sized trees of good potential that remain. The guiding principle followed in this kind of cutting is the concept of financial maturity, which is applied with careful attention to the quality of increment as well as to volume. Full advantage is taken of the excellent natural pruning of some of those remnants of earlier stands that are capable of regaining full vigor (Fig. 13.11). This procedure rehabilitates the stands and preserves enough of the irregularity of the initial stands that some intermingling of age classes remains.

A US Forest Service experiment at the Crossett Experimental Forest in Arkansas developed some long-term trials with mixed loblolly and shortleaf pine stands. Although both species are shade intolerant, their advantage is that they periodically produce seed that can establish on disturbed seedbeds. Seedlings establish and grow when released from either competing understory vegetation or overtopping trees. The overall approach is to regulate the stocking and diameter distribution of the merchantable timber, and to vigorously control hardwood and herbaceous competition with the use of broadcast herbicide (Shelton and Cain, 2000). Guidelines require residual basal areas of 44–60 ft^2/acre (10–14 m^2/ha), maximum diameters of 14–22 inches (35–55 cm) DBH, and a q-factor of 1.2 after harvest (Cain *et al.*, 1996; Shelton and Cain, 2000). Stand basal areas that exceed 73 ft^2/acre (17 m^2/ha) need to be avoided because seedlings fail to establish and show poor growth because of overstory shading and root competition.

This kind of approach has helped meet the need for silviculture on small, private, non-industrial ownerships that include almost two-thirds of the southern forest (Williston, 1978; Murphy, Baker, and Lawson, 1991). The chief emphasis tends to be on manipulating existing growing stocks in order to extract optimum advantage from them over the longest possible time. Although regeneration is seldom perfect, it is often possible to get sufficient natural regeneration, if fire, herbicides, browsing, and harvesting of hardwoods, are used to keep the hardwoods under some degree of control.

Oak–Hardwood Forests of Eastern North America

Most oak–hardwood forests are managed with the purpose of securing advance regeneration of oak by the use of shelterwood methods. This is particularly the case where there are more shade-tolerant hardwoods in competition with the oaks for the same understory growing space. The use of preparatory treatments (fire, herbicides) is necessary, or the use of opportunistic establishment or seed-tree cuts that take advantage of masting (see Chapters 9, 10). The strongest example of failure is the single-tree selection trials of Appalachian oak forests (Keyser and Loftis, 2012). Improvement cuttings conducted over a half-century following the Bdq method to regulate the mid-story canopy of shade-tolerant trees failed to regenerate the more shade-intolerant oaks, such that after this time there was little difference between the unmanaged control and the selection treatments, with increasing dominance of the shade-tolerants in all strata. Group selection systems applied on these same kinds of forests where oak competes with shade-tolerants can be more promising and more applicable for small private landowners (Miller, Schuler, and Smith, 1995) (Fig. 13.12). In treatments applied to even-aged second-growth forests in the central Appalachians of West Virginia, openings of at least 0.5 acre (0.2 ha) need to be made with

(a)

(b)

Figure 13.11 **(a)** A stand that is predominantly of loblolly and shortleaf pine, being managed under the single-tree selection system at the Crossett Experimental Forest, US Forest Service, southern Arkansas. The large-branched pine (in front of the man in the picture) will be cut to foster the growth of the small-branched tree behind him. *Source:* Yale School of Forestry and Environmental Studies. **(b)** An example of group selection for loblolly and shortleaf pine with hardwood control at the Crossett Experimental Forest, southern Arkansas. *Source:* John D. Hodges, Mississippi State University, Bugwood.Org. Reproduced with permission from Bugwood.org.

Figure 13.12 A group/patch selection for oak–hardwood forest on a mesic site where competition exists with more shade-tolerant species on a stand at the Yale–Myers Research and Demonstration Forest in southern New England. Site treatments included crushing laurel brush, chopping and crushing slash, and partly scarifying the soil. Individual trees have been left purposely in the openings to provide more structure and food for wildlife, and as a seed source for oak regeneration. *Source:* Yale School of Forestry and Environmental Studies.

some free-form thinning between the groups. All trees greater than 1 in (2.5 cm) DBH need to be cut in the openings to promote the shade-intolerant species over the existing shade-tolerant understory. Standing basal areas of sawtimber after treatment need to be maintained between 55–85 ft^2/acre (240–370 m^2/ha) depending upon poor or good sites respectively (Miller, Schuler and Smith, 1995).

However, selection methods can be used where oak is competitive, usually on drier sites or climates of the midwest. A successful example can be seen in the Ozark Highlands, Missouri (Loewenstein, 2005). Stands that were even-aged second-growth forests in 1961 have, over this period of time, been converted to balanced uneven-aged structure by allocating growing space to the overstory, midstory, and understory at a ratio of 3:2:1, using a q-factor of 1.7 for 2 in (5 cm) diameter classes, and maintaining about 60% of the basal area in the overstory sawtimber size class. The q-factor is taken as an approximate guide and more attention is paid to ensuring that each spatially defined, even-aged stratum or cohort (understory, midstory, and overstory) is provided sufficient growing space to develop. The procedure is similar to one adopted in the Mississippi bottomland for cherrybark oak by the Anderson Tully Company, but the cutting cycle and nature of this oak forest is very different (Fig. 13.13). Shade-intermediate pine and shade-tolerant hemlock with a hardwood component of maple and birch can be managed with a balanced age-class distribution through group selection on the right sites (Fig. 13.14a); under the wrong site conditions it can fail (Fig. 13.14b).

Northern Hardwood Forest of Northeast America

Northern hardwoods are probably the most appropriate of all the hardwood forest types to apply selection systems, given their relatively species-poor composition and their dominance of beech and sugar maple. Disturbance regimes in northern hardwoods include mostly release-type disturbances from convectional windthrows, occasional tornadoes, insects, and disease. The region spans Minnesota to Maine, and from Ontario to northwest Pennsylvania. The past cutting histories parallel those of the US west coast. Initially, these forests were selectively cut (high-graded) for the best timbers, but with the industrialization of the American economy in the the late 1800s, many of these forests were heavily cut over for charcoal and chemical distillates. Extensive forest areas have now been traded by the large private pulp and paper companies to timber investment

Figure 13.13 A single-tree selection system for bottomland oak. A photograph depicting cherrybark and Nuttall oak that is managed on a single-tree selection system on former Anderson–Tully land in the Mississippi floodplain. Three to four balanced age classes exist, with each age class managed on a 40–50-year rotation. The photograph shows larger trees that are about 35 years old in intimate mixture with a pole-sized age class of about 20 years old and a regenerating age class of about 5 years. Establishment cuts both harvest the oldest trees and establish the new cohort. A release cleaning is done to the regeneration after harvest. The stand is purposely maintained in an open condition to ensure the upward growth of all below-canopy cohorts. *Source:* Mark S. Ashton.

management organizations (TIMOs). The structural conditions of many of these forests are poor, dominated either by young even-aged, second-growth stands, areas of irregular structure, or stands mainly of beech and red maple.

Researchers in four main areas of northern hardwood forest have developed selection systems: (1) New Hampshire; (2) the Adirondacks; (3) Quebec; and (4) the Upper Peninsula of Michigan and Wisconsin. In New Hampshire, work by Leak and his colleagues (Leak and Filip, 1977; Leak, Solomon and DeBald, 1987; Leak, 1999) have demonstrated, over a 70-year period, the use of the hybrid group and patch selection method for both maintaining species composition and creating an irregular structure that creates approximately four balanced age classes over the course of the development of the stands. The openings vary in size from small groups to patches, but they average 0.5 acre (0.2 ha). Creating larger openings than single trees maintains 25–33% of the composition in shade-intolerants (paper birch, yellow birch, and white ash). Standing dead trees make up about 20/acre (50/ha) with about 3/acre (8/ha) that are sawtimber size (Leak, 1999). These systems can maintain the diversity and composition of breeding birds found within old closed-canopy northern hardwood forests (Costello *et al.*, 2000). Keeton (2006) went further with work that was modeled upon leaving larger trees, but creating some smaller gaps along with larger ones, creating greater numbers of snags and greater amounts of downed debris. His model predicted that this kind of enhanced structure can be maintained into the future, although this has yet to be demonstrated in the long term.

Work in the Adirondacks by Nyland and colleagues using a balanced uneven-aged single-tree approach can sustain pure beech–sugar maple stands on a 12–15-year cycle (Mader and Nyland, 1984), but where beech dominates over sugar maple, control of understory beech is necessary, and herbicide application is used (Jones, Nyland, and Raynal, 1989; Nyland 1998). Diameter distributions of beech and sugar maple created in the selection system resemble that of old growth (Kenefic and Nyland, 1999). Compared to diameter-limit cutting, selection systems applied to Adirondack forests have higher present net worth in the long term. Diameter-limit cuttings are only beneficial from short-term gains in timber value (Nyland, 2005).

In the Upper Peninsula of Michigan and in Wisconsin, sugar maple forests are largely made up of cut-over, second-growth stands (Crow *et al.*, 2002). Mechanisms to increase greater structural and compositional diversity can be done by opening the canopy and disturbing the groundstory, to encourage more shade-intolerant species and to release smaller trees and shrubs. Too many larger openings 0.10–0.20 acre (400–800 m^2) promoted yellow birch, and combined with ground scarification, can promote trembling and bigtooth aspen (Crow *et al.*, 2002). To promote eastern hemlock, openings of 800–1000 ft^2 (80–100 m^2) made by felling single trees are more desirable, as long as browse pressures are low (Webster and Lorimer, 2002). Forests managed with single-tree selection systems in this region have cutting cycles that are 10–20 years, post-harvest residual basal areas that are 70–80 ft^2/acre (16–18 m^2/ha), and maximum tree diameters that are 18–22 in (45-56 cm), with some land managers using the BD*q* method (*q* 1.3) (Schwartz, Nagel, and Webster, 2005; Neuendorff *et al.*, 2007). The smaller opening size and the lack of scarification tends to promote a single-species sugar maple forest, with a range of

(a)

(b)

Figure 13.14 (a) A group selection system for white pine–hemlock at the Yale–Myers Research and Demonstration Forest in southern New England. The stand is being managed for balanced age classes. The centers of the openings were purposely selected over the top of sites where advance regeneration had been established. Site treatments included crushing and chopping slash around the edges of the opening, and some scarification was done where possible, but protecting advanced regeneration in the opening centers. Although oak is in the canopy, the openings are too small and advance regeneration is too sparse to establish oak regeneration with the more shade-tolerant and faster-growing hemlock and pine. (b) Canopy openings that failed to regenerate white pine–hemlock using group selection because of an absence of advance regeneration to work with within the openings and a failure to scarify the soil and remove the fern competition to make new growing space available for further recruitment. *Source:* (a, b) Mark S. Ashton.

reverse-J diameter distributions (negative exponential, increasing q-ratio, and rotated sigmoid) (Neuendorff *et al*., 2007). These same arguments are made by Angers *et al*. (2005) for northern hardwood forests dominated by sugar maple in southern Quebec. This can be remedied by some scarification, larger gap opening size, and removal of beech, with brush cutting where it predominates in the understory (Bédard *et al*., 2014). To encourage more single-species yellow birch stands, research suggests that patch selection with scarification is best (Prévost, Raymond, and Lussier, 2010).

Acadian Spruce–Fir and Maritime Boreal Forests

Balsam fir and red spruce dominate the higher elevations of Maine, New Hampshire, Quebec, and the Canadian Maritimes (New Brunswick, Nova Scotia, and Labrador). Work by Brais *et al*. (2013) demonstrated that both single-tree and group selection methods can regenerate trembling aspen and balsam fir. A long-term experimental study under the Acadian Forest Ecosystem Research Program in central Maine found that small openings of less than 0.25 acre (0.1 ha) favored late-successional red spruce and eastern hemlock, while large openings of more than 0.25 acre (0.1 ha) favored white pine and red maple (Arseneault *et al*., 2011). Based on these studies and work on defining natural disturbance regimes within the northeast (Seymour, White, and deMaynadier, 2002), group selection systems with retention of reserves in the openings can be done at relatively frequent periodic intervals, reflecting a 1%/year disturbance rate. These systems are designed to create greater structural and compositional diversity for single-species stands that are homogeneous and heavily cut over (Seymour, 2005) (Fig. 13.15). Coarser variations have been suggested with condensed forest entries over a shorter period of time as irregular group shelterwoods (see Chapter 11 for details).

In the poorly aerated peat swamps of the northern forest, regeneration of black spruce and northern white-cedar by natural layering is an important supplement to that from natural seeding, and is encouraged by developing uneven-aged stands. Because the layering takes place only when the ends of live branches are overgrown by sphagnum moss, it is essential that tree crowns touch the ground in a sufficient number of places. This condition can be maintained only in uneven-aged stands (Johnston, 1977). The sites are poor enough that the stands often do not close, and the rise of water-table levels that would result from reduced transpiration after clearcutting might harm the trees. The partially cut stands are surprisingly

Figure 13.15 A variable single-tree to group selection in Acadian spruce–fir forests on the Penobscot Experimental Forest, Maine. *Source:* D. Maguire, Department of Forest Engineering, Resources and Management, Oregon State University, Bugwood.Org. Reproduced with permission from D. Maguire.

resistant to wind, because the peat is so resilient that the force of the wind tends to be dissipated in agitating the soil itself, rather than in damage to the trees.

Tropical Rainforests

Selection systems applied to tropical rainforests are completely different phenomena from the more sophisticated systems that have been described above. Most of the so-called selection systems are actually little more than diameter-limit cuttings that are a first approach to imposing some kind of silviculture in a forest that is largely being high-graded (Fig. 13.16). The difference with temperate-forest diameter-limit cutting is that in tropical forests there are over 20 species/acre (50 species/ha) to try to keep track of, with all the species growing at different rates, maturing at different times, and exhibiting different growth habits (Ashton and Hall, 2011). As would be expected, single-tree selection systems would be most appropriate for the shade-tolerant, single-species rainforest types, but it seems no systematic thought has been given to different silvicultural approaches to the wide range of forest types and species compositions within a vast climatic region.

The oldest selection systems employed in the tropics actually were implemented by American foresters in the Philippines in the 1950s, imitating the selection systems being applied to coastal Douglas-fir in the Pacific Northwest from 1930 to 1950 (Reyes, 1968; Appanah, 1998). The system was designed for mixed dipterocarp forest with the intention of leaving 70% of all dipterocarp timber trees 8–24 in (20–60 cm) after removing the larger dipterocarp timber trees greater than 24 in (60 cm) DBH. This required follow-up treatments that liberated advance regeneration and cut the lianas. Unfortunately, even these simple guidelines were not followed and at each entry the forest was over-cut and degenerated into thickets and scrublands. Malaysia followed with its own selection system in the 1970s for hilly mixed dipterocarp forest. Indonesia then followed Malaysia in the 1980s. Both countries adopted almost the same guidelines, initially removing all trees greater than 24 in (60 cm) DBH but then targeting all trees greater than 20 in (50 cm) DBH. Cutting cycles were set initially set at 15-year intervals, then 30, and now between 40 and 60 years (Sist *et al.*, 1998). Many of these forests have now been defined as “degraded” and are cleared for oil palm plantations. Some of the most timber-productive tropical forests in the world are now dominated by vines and pioneer second growth.

The logging in the Amazon from the 1980s onward, and more recently in Central Africa beginning in the 1990s, holds similar stories particularly in association with the mahogany family (*Meliaceae*). For example in the *Entandrophragma* spp. (*Meliaceae*) dominated forest of Central Africa, Hall *et al.* (2003) demonstrated the degradation of commercial timber species and shifts in forest structure and composition through selective logging.

The only proven true selection–regeneration method that has been developed is the CELOS system in Suriname, designed for relatively shade-tolerant forests of *Mora excelsa*, *Ocotea* spp., and *Peltogyne venosa* (De Graaf, 1986). In the CELOS system, cutting intervals vary from 20–30 years depending upon site. Harvests extract 700–1400 ft^3/acre (20-40 m^3/ha) of timber, and are followed up with thinning and liberation treatments (see Chapters 20, 21) (De Graaf, Filius, and Huesca Santos, 2003).

(a)

(b)

Figure 13.16 **(a)** Diameter-limit logging under the guise of the Malaysian Selective System applied to hill dipterocarp. Chronic repeated cuttings have reduced the structure and composition of the forest to a liana-infested stand in Sarawak, Malaysia. *Source:* Mark S. Ashton. **(b)** Repeated diameter-limit cutting in bottomland oak forests of the Mississippi floodplain has removed the overstory oak and converted the stand to shade-tolerant hardwoods and vines. *Source:* US Forest Service.

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Part 3B

Methods Based on Artificial Regeneration

Information on the collection, treatment and propagation of seeds and vegetative systems, and their temporal and spatial arrangement in plantings.

14

Species Selection and Genetic Improvement

Introduction

When planting, the silvicultural goal is to select the right tree for the right place with the right amount of growing space at each stage of development. This requires careful knowledge of the site (see Chapter 3). It also demands very careful selection of species to meet the constraints of the site, and simultaneously accommodate the desired social values and outcomes of planting the tree (i.e., aesthetics, watershed protection, timber, or shade).

Therefore, a decision must be made along the continuum between the species type and the degree of site modification required. On one end of the continuum is the view that stands should consist of the species and genotypes best adapted to survive and reproduce on the site after many generations of natural selection. However, the specific evolutionary attributes that enhance the species' survival in nature do not necessarily satisfy human social values. Furthermore, the natural forest composition is dynamic and subject to continual changes resulting from developmental processes initiated by competition or natural disturbance. Even if the natural composition perspective is accepted, the choice of which developmental stage to imitate still needs to be decided. Another problem with this approach is that human disruptions have made it very difficult to know what natural compositions might have been in many locales and the future changes in climate make selections based on an original baseline fabricated (see Chapter 3 for details and a discussion on this topic).

At the other extreme is the view that silvicultural prowess and engineering can make human wishes concerning species composition come true, as is the case with much of modern-day agriculture. However, problems such as getting trees, shrubs, and other woody perennials to survive through dormant seasons when the species are not in their native sites cause foresters to stop short of fully emulating the agronomy of herbaceous annuals. For example, maize from Central America can be moved to Minnesota, but the same cannot be done with Honduran mahogany. In fact, trembling aspen cannot be safely moved from a moist site to a dry one within a Minnesota farm woodlot. Therefore, it is unusual in forestry that species would be selected that are so unsuited to a planting site that the site actually has to be significantly modified by irrigation, drainage, or soil nutrition to ensure planting survival. If this occurs, it is where people can afford to spend a good deal of effort controlling site factors because the social and economic values of the species are so desirable, but this often has environmental repercussions in the long term. Such practices are much more common in agricultural and urban systems where social values are considered much more important and where people are willing and able to spend more money to ensure the right trees are planted. In this case people have dictated what to plant and the site factors are often of a secondary consideration.

Because neither natural factors nor human desires can be ignored, the most logical choice lies between these extremes and depends upon the particulars of social value and biophysical circumstance. Three steps should be taken when selecting a species to plant. The first step is to determine the environmental limitations of the site and its potential for amendment (e.g., through fertilization). This restricts the potential number of species. The second step is to choose the species (plural or singular) that will most nearly meet the human objectives of stand management. The third step is to consider the degree of artificial control that will be exerted over the genetic constitution of the selected species. This may range from simply accepting the existing genetic makeup of a species, to using intensive breeding methods to develop more desirable genotypes.

The basic objective is to use genetic material that will survive and thrive on the site, and also yield the maximum social benefits. However, suitable "genetic material" is seldom any single genotype. Even if only one single species is used, it is best to maintain some degree of genetic variation within each stand. The best choice may also be a combination of many species. Ultimately, the choices that are made with respect to the matching of species and site will affect and interact with decisions about the entire program of silvicultural treatments that will be devised.

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

Selection of Species and Provenances

Adaptation to Site

The first consideration in determining which species to grow is the degree of their adaptability to the site. The most logical choice is the region's **native species**, and whose natural ranges include the site in question. These species have specifically adapted to their environment over time. However, the native choice favors the perpetuation of their own kind, which does not necessarily include high production rates, stem straightness, fruit form and size, or any other human-desired attributes.

It is also possible to bring in species from other areas. These are called **exotic species**, if planted outside of their natural range. Many people confuse exotics and invasives. Exotics can be invasive, but most introduced exotics are not invasive. Confusion also exists about this term because it is sometimes used to denote movement of species across national boundaries, but that distinction is not very useful. The natural range of a species, controlled largely by climatic and soil conditions, is the most important criterion. By either definition, eucalyptus grown in California is an exotic; Douglas-fir seed from Canada grown a short distance away in the US is not an exotic in the ecological sense. Sometimes, a species is extended beyond its range but not into an entirely new area. An example of this is the range of red pine being extended south from its natural limit throughout the northeastern US. Such species are often referred to simply as **non-native**, but they are exotic in terms of ecological and silvicultural management considerations.

Thus, there are three basic alternatives in choosing species: (1) use the native species adapted to the local climate; (2) introduce exotic species from distant places with similar climates; or (3) move non-native (exotic) species relatively short distances beyond their natural range. Dramatic movements of species across major geographic barriers have been more successful than seemingly modest extensions of their natural ranges. Obvious examples of timber trees are Monterey pines that are native in Southern California, and slash pines that are native to the US south. These two species were introduced into New Zealand, Argentina, South Africa, and Chile. Eucalypts, originally from Australia, were introduced almost throughout the freeze-free regions of the world. Intercontinental movements ideally place the species in a location where they were adapted to grow, but had been prevented from doing so only from their separation by oceans or inhospitable land surfaces. Conversely, extensions of the natural ranges of some American conifers by distances of 100 miles or less have sometimes proven to be either marginally successful or highly unsuccessful. This has been true of the southward extension of the range of red pine and the northward movement of loblolly and slash pine (see the Exotic species sub-section of this chapter). Reasons for this usually relate to climate stressors limiting the species' original range, and secondary effects of native insects and disease.

It is also important that the individually selected species will not only survive on the proposed site, but will also grow well, and more competitively than others. This consideration should not only include growth rates in average conditions, but also tree performance during periods of climate extremes such as droughts and cold temperature. In most cases, trees must survive long periods of seasonal changes in temperature and precipitation. Events such as the coldest day of the century, infrequent outbreaks of defoliating insects, rare severe fires, or bad windstorms must be anticipated. For the forester, these should not be surprises but events, that with careful forethought, can be planned for by selecting the most hardy species resistant to these unpredictabilities. What happened once can and probably will happen again, particularly in this age of climate change and instability. In addition, species choice is dependent upon soil conditions. This is where the site-classification techniques described in Chapter 3 become important and must be considered.

Utility of Species for Different Objectives

Although often ranked as the first consideration, a species' utility or social value is secondary to its adaptability to site. Difficulties commonly arise if one species is planted all over the region because its timber brings the best price at the time of planting. Some of the worst problems that are accredited to "monocultures" derive from this approach.

However, there are reasons to favor particular species from among those that are well adapted to a site, based on their utility for wood and paper products, for their values as a non-timber product (fruits, medicinals, cordage, and fodder), their ability to endure the stress of urban environments, their use as nurse trees to provide shade in agroforestry systems, or for their hydrological value in slope and stream stabilization. Species can be categorized into ecological groupings, and for thousands of years people have taken advantage of these groupings to select for particular commodity and service values (see Table 14.1). It is not by chance that most of our preferred beverages (coffee, tea, hot chocolate) are understory trees and shrubs, or that most of our temperate street trees in cities are originally from the floodplains of large rivers. Humans have a long history of choosing conifer species over angiosperms for timber. One important reason for it is that evergreens are more productive than deciduous trees in many temperate and boreal climates and sites. Conifers also have an excurrent growth form, with a greater proportion of the wood produced

Table 14.1 Utility and service values in relation to species ecological category.

Ecological category	Utility/service value
Short-lived pioneers of the initiation stage	Shade trees in agroforestry; nitrogen-fixing trees improve soil fertility; erosion control; light specialty wood (e.g., balsawood); carbohydrate food crops
Long-lived pioneers of the stem-exclusion stage	Construction woods; pulp and paper fiber; resins and latex (e.g., rubber)
Canopy dominants of late succession	High-quality furniture, flooring, and specialty woods (e.g., carving); resins and saps; nuts
Canopy non-dominants of late succession	Large rich/oily fruits; high-quality dense woods (e.g., durian, mango, avocado)
Sub-canopy species of late succession	High-quality fruits and medicinals, spices (e.g., mangosteen)
Understory species of late succession	Beverages, medicinals (e.g., coffee, tea)

Source: Mark S. Ashton.

being contained in a single central stem. This is in contrast to the more decurrent form of many angiosperms, where most of the tree's wood production is contained in the large branches forming the crown. Conifer stems also tend to be straight, whereas the stems of many angiosperms bend toward gaps in the canopy (See discussion in Chapter 17 on geotropism: single dominant stemmed; and phototropism: multiple-stemmed).

The differences in wood anatomy among species give each a unique set of characteristics for use in wood and paper products. There are some common wood properties that should be considered (Box 14.1). For more details, see wood technology books by Panshin and DeZeeuw (1980), Hoadley (1990, 2000), Bergman *et al.* (2010). Specialty uses exist for nearly every kind of wood, but the main commodity uses are: (1) solid wood for buildings and furniture, and (2) paper and cardboard for packaging and printing.

The very simplified discussion of wood technology is included here mainly to demonstrate that certain conifer species have characteristics that have made them highly useful for producing the basic commodities of building materials and paper products (Box 14.1). This is one of the drivers behind the conversion of large areas to conifers. Another factor is that conifers are better than many hardwood species at growing in disturbed sites or with highly competitive grasses. In parts of Europe and Great Britain, deforestation of the native forests for agriculture was followed centuries later by afforestation, which shifted a natural deciduous forest to conifers. The obvious natural parallel to this is the "old-field pine" phenomenon in the eastern US, where conifers were the first to colonize open agricultural areas, allowing the second-growth hardwoods to come in only later. Forest industries developed where these conifers occurred. This created the white pine industry of the northeastern US in the early part of last century, and the southern pine industry in the southeastern part of the nation in the second half of the last century. Exotic conifers have been introduced to parts of the world that are lacking such species, but where the same land-use histories made conifers temporarily competitively adapted to climate and circumstance.

Fortunately, technology has increased efficiency of wood utilization. This has made use of wood continually more versatile and less species selective. A shift has occurred from demand for certain wood properties of conifers, to supplying a much wider range of tree species. This technological shift has occurred mostly during a 50-year period (or shorter), which is approximately the length of a rotation of fast-growing temperate species. This illustrates an important point – that wood utilization tends to change faster than foresters can change the forest composition. Products are continually being made from trees that have been regenerated with a different goal in mind. Consequently, it might be best to grow species that are adapted to a particular site, choosing from among the inherently useful species that grow there.

There is always the risk that any chosen species may fall completely from favor. However, this actually happened only when the utility of the wood was limited to specialized purposes. For example, some of the first silviculture in America was based on the fast growth of insect-deformed, branchy, eastern white pines growing on abandoned agricultural lands in New England. The wood was good for making wooden boxes, but not much else. Technology drove a shift from wooden boxes to cheaper corrugated boxes made from brown Kraft pulp. In contrast, the market for good white pine lumber remains excellent. It is therefore unwise to only grow trees of species that are of such poor quality or small size that their use is limited to some very specialized purpose. Perhaps hard pines should not be grown in ways that make them suitable only for pulp for making cardboard boxes. Similarly, potentially high-quality hardwoods should not be grown in ways that limit their use to burning for industrial biomass for energy production.

It would be wrong to focus on these large-scale commodity uses to the exclusion of others. For much of the world, fuelwood for home heating and cooking is the most highly valued wood product. Coppice systems are the best way to manage this demand, because high-density hardwoods with low moisture content sprout vigorously

Box 14.1 The technology of wood and species selection.

For solid wood products used for structural purposes, wood density is the single most important characteristic because it controls load-bearing strength. It is generally expressed as specific gravity, which is the ratio of wood density to the density of water. At specific gravities below 0.30, wood is not strong enough to be used for most building construction purposes. Wood in the range of 0.40–0.55 is ideal for such purposes because it has adequate strength, but is not so heavy that it cannot be easily transported and milled, or nailed and cut with hand tools or small power tools. Strength and durability to denting and scratching increase significantly above specific gravity of 0.60, but these woods are no longer as easy to work with. Above levels of 0.80, there are serious limitations to machine milling and sometimes even to felling the trees (Hoadley, 2000).

Conifer wood has a transition within each annual ring from low-density earlywood with large thin-walled cells to high-density latewood with thick cell walls. The strength of different species depends primarily on the density of the latewood. Species with the highest density, including Douglas-fir and many species of hard pine, are ideal for framing lumber and plywood. These species have the structural design of an engineered composite, in which sheets of dense material are embedded in a low-density matrix, producing a strong material that can still be easily milled, cut, and nailed. Other conifers, such as spruces, firs, and hemlock, have latewood of lower density. This gives them lower overall strength, but they are still useful for many structural purposes. A very mild transition from earlywood to latewood density is found in such species as the soft pines and western redcedar. These are generally not used for structural purposes, but they are easily machined and are important where load-bearing strength is not the primary consideration. Soft pines are prized for furniture and interior finish, and the rot-resistant properties of western redcedar make it valuable for uses where it will be exposed to the elements, such as exterior home siding.

Many of the most useful hardwood species produce wood with a density somewhat greater than that of the high-density conifers. Diffuse-porous species and tropical species lacking growth rings also have a more uniform density within each growth ring. Wood of this density, from such genera as oak, maple, beech, teak, and some members of the *Eucalyptus* genus, is used for flooring and furniture, where durability is required. Some tropical species of even higher specific gravity are used only where minimum millwork is required, such as for industrial flooring, railroad ties, and construction, where extraordinary strength is needed.

Hardwood trees of small diameter or poor stem form that cannot be used for the markets described above have often been under-utilized. They are useful for pallets, barrels, and crating, but these markets are so limited compared to the supply of such trees, that it is often difficult to recover the costs of removing these trees in thinning. Some hardwood species also have wood that is too low in density for many uses, but this problem appears secondary to that of size and form. For example, yellow-poplar has been used for a variety of purposes over the years, in spite of its relatively low density. Its utility is increased by the fact that it has a conifer-like excurrent growth form with large straight stems and rapid growth.

The development of engineered solid wood products, in which chips are reconstituted into panels and framing lumber, has increased the use of small trees, and has opened the possibility of using hardwoods of low density or poor stem form such as aspen poplar and red maple, which for many years had low timber value. The uniform density of the wood of these diffuse-porous species is favored for some of these products because of the uniform chip quality produced.

The production of paper from wood fibers depends on somewhat different properties of wood. It should be noted that in wood technology, the term *fiber* is used for both the fiber cells in angiosperms and the tracheids of conifers. The strength of paper depends on having long fibers with relatively thin cell walls, which allows the cells to collapse during the paper-making process. In a sheet of paper, wood cells lie in a random arrangement like pine needles on the forest floor. Pulp that is composed of long, flattened cells with most of the lignin and any resins removed, produces the strongest cellulose bonds between cells, and thus the strongest paper. Conifers have a distinct advantage in cell structure because conifer tracheids are longer than hardwood fiber cells, and their cell walls are generally much thinner.

Among the conifers, those species with latewood of lower density have cells that collapse more easily. When paper was first made from wood on a large scale, it could only be done from species with long fibers, moderate to low density (thus thin cell walls), and very low resin content. Spruces and true firs fit these criteria, and were the chief species from which paper was made. Paper-making initially was done by mechanical pulping but the strength of this paper was limited by the lignin content which interrupted the cellulose bonding. Mechanical pulping of these species is still widely used for producing newsprint.

Much paper is now made from the fibers of hard pines, but this was impossible for a long time, because of the high resin content and the high proportion of thick-walled latewood cells that resisted collapse. Only by the development of two processes was it made possible: (1) the Kraft method of chemical pulping, which used alkaline solutions not only to remove resins, but also to convert them into turpentine and other useful chemicals; and (2) mechani-

Box 14.1 (Continued)

cally "beating" the pulp, which partially shreds the outer layer of cellulose of the cell walls, thus giving greater surface area for inter-cell bonding, which compensates for the cells' resistance to flattening. The development of these processes in the middle of the 20th century had great impact by allowing the use of the long fibers of hard pines and Douglas-fir. This resulted in strong brown paper and corrugated cardboard that could be used for packaging, and an industry developed to turn hard pines into such material. Pulp made by the Kraft process can also be bleached to produce white printing papers. These high-density species are so valuable for solid wood products that paper making is not necessarily the most logical principal management objective for them but it is a valuable outlet for thinning and sawmill residue.

These advanced pulping technologies also made it possible to make paper from very thick-walled fiber cells of hardwoods. Because these fibers are short, paper produced from hardwood fibers alone is not strong, but a mix of long conifer and short hardwood fibers can produce an adequately strong, fine-surfaced paper, the kind of which this textbook is made. The use of papers for printing has increased so greatly that the world demand for hardwood pulp is approaching that for conifer pulp.

from stumps or roots (see Chapter 12 on the coppice regeneration method). There is also great interest in choosing **multipurpose tree species** for use in agroforestry. In this case, the ideal species would produce wood that is useful for fuel and light construction, foliage that is highly nutritious for livestock, and fruits for humans.

Frequently, the choices do not revolve entirely around the species themselves, but around the stage of natural succession or natural stand development to be maintained. In general, later stages will be easier to maintain, but some earlier stage may have more productive or valuable species. The choice can also be viewed as that of an assemblage of species, both plant and animal, with pests and parasites included, representing some stage of vegetational development, and not just a species for timber, shade, or aesthetics. The choice of successional stage or particular stand structure usually meets most objectives in watershed and wildlife habitat management. Sometimes, though, favoring a particular tree species or genus is necessary. Such choices are discussed in the chapters devoted to those management objectives (see Chapters 24 and 29).

Selection of Provenances

Many species extend over such wide geographical ranges that, as a result of natural selection, they evolve different forms suitable in different environments. The genetic variation within a species may occur as a continuum across the range. Where the range has been broken up by barriers, such as mountain ranges, it may occur as distinct ecotypes. Ecotypes are distinct in their geography, morphology, and genetics. In either case, the geographical origin of a seed is called its **provenance**. If ecotypes develop, they are recognized as **subspecies** or **varieties** (no clear distinction exists between these two terms), which are formally described and given Latin names. For example, lodgepole pine has three recognized subspecies: *Pinus contorta* ssp. *contorta* on the Pacific Coast, *Pinus contorta* ssp. *murrayana* in the Cascade and Sierra Nevada Mountains, and *Pinus contorta* ssp. *latifolia* in the Rocky Mountains. Where ecotypes are less distinct, they are referred to as **races**, and are usually given a name associated with their geographical location (Fig. 14.1). Environmental adaptations do not cause all of the variation among provenances. Some appear to be the result of more random processes.

As is the case with species, the safest provenances to use are usually the indigenous ones found on the site or within the area. If a native species is being used, there is usually the temptation to bring in seed from a provenance of more favorable climate. In general, trees from lower elevations, lower latitudes, or regions of higher precipitation grow faster when moved to higher elevations or latitudes or regions of lower precipitation. However, the more rapid growth comes at the expense of increased risk of damage. This is because trees growing in harsher climates have adapted to those conditions by developing specialized adaptations, such as early stomatal closure during periods of water stress or very early bud set and cessation of shoot elongation. These characteristics reduce photosynthesis and growth, but also favor survival. Moving provenances adapted to moderate conditions may produce more rapid growth for considerable periods, but then when predictable climatic extremes occur, the plants will suffer outright damage from cold or drought, or reduced vigor leading to insect or disease attack. Successfully using the faster-growing plants may depend on whether thinning, weed control, fertilization, or some other treatment will reduce these effects. Rules have been developed for some species regarding the safe distance to move seed in elevation or latitude. Sometimes, general guidelines exist, suggesting that seed can be safely moved up to 100 miles (160 km) in latitude or 1000 ft (300 m) in elevation. These guidelines are actually only useful for indicating the order of magnitude of such limitations, because they will differ for each species

(a) (b)

Figure 14.1 Foliage characteristics of two distinct races of ponderosa pine. **(a)** Open plume-like arrangement of long, slender needles of North Plateau race from eastern Oregon. **(b)** Compact, brush-like arrangement of short, thick needles typical of race found east of the Continental Divide from Colorado northward. The needles shown in **(b)** are more resistant to frost and winter injury than those in **(a)**. *Source:* **(a, b)** Yale School of Forestry and Environmental Studies.

and location (Zobel and Talbert, 1984; White, Adams, and Neale, 2007). For example, Douglas-fir is specialized in its adaptation to local climate in the northern Rocky Mountains, whereas western white pine is much more genetically homogeneous across its range for the same region.

Exotic Species

Exotic plant species are used widely in agriculture, horticulture, and landscaping. They are not generally used in forestry unless with reforestation enterprises. Though their use is less widespread in silviculture, they dominate forest management in some regions of the world. The principles of using exotic tree species in silviculture have all been reviewed (Zobel, van Wyk, and Stahl, 1987; Evans, 1992); White, Adams, and Neale, 2007).

Generally, an introduced species should come from a locality whose climate and soils are similar to those of the home region. A site's latitude and position on the continent are the main controls of its climate. Climate can be further defined by the following quantitative parameters: (1) mean annual temperature; (2) mean maximum temperature of the hottest month; (3) mean minimum temperature of the coldest month; (4) mean annual rainfall; (5) rainfall regime (uniform or seasonal); and (6) length of any dry season. These parameters have proven useful for mapping areas of the world suitable for particular tree species. They identify both average conditions and climatic extremes that may cause damage to trees. Matching soils can also be important, because moving species to extremely different soil types from which they naturally grow in (e.g., from acid to basic soils or from clays to sands) may cause problems. This becomes more important in the tropics where soil weathering processes can be very pronounced across even small changes in topography and geology (Hall *et al*., 2004).

Exotics have been used largely to supplement the native species in areas that naturally have low species diversity. For example, conifer species have been planted in regions where they are few or entirely lacking. In regions with large varieties of native species (particularly in the tropics), a few well-known exotic species have been used to replace the native forests to simplify silvicultural techniques. The latter practice is more difficult

to defend ecologically than the former. Use of exotics in the tropics can usually be attributed to their familiarity, strong and known commodity market, high silvicultural knowledge base, and ease of cultivation, in comparison to so many tropical species that are poorly understood and unfamiliar (Wishnie *et al*., 2007).

The use of exotics in North America is limited because every region of the continent has many species from which to choose. Rather, North America has been important as a donor region. Many conifers from the west coast of North America have been remarkably successful at the same latitudes in western Europe. Douglas-fir, Sitka spruce, and lodgepole pine are among the most common species used. Though no longer the case, they were used in Great Britain, Ireland, and parts of Sweden in reforestation programs for a large portion of the past century. The forest economies of many countries in the warm temperate and subtropical regions of the southern hemisphere are heavily dependent on slash, loblolly, jelecote (*Pinus patula*), and other pine species introduced from localities of comparable climates in the southern United States and Mexico.

The single most widely exported tree species in the world is radiata (Monterey) pine. This species is native to a few small areas on the coast of California. Low precipitation levels or low winter temperatures have limited it from expanding into adjacent areas. It is planted in the southern hemisphere in Australia, New Zealand, Chile, and South Africa, but has thrived only in places with the same general climatic pattern of California's coast. Monterey pine is an example of an exotic that can grow better in the new environment because the climate is more favorable than the native one. The territory suitable for exotic Monterey pine is much larger and often has more rainfall than the small parts of California to which geologic events have confined it. The vast oceans of the southern hemisphere provide a mild climate that is very favorable to this and other tree species from the more harshly variable climates of the northern hemisphere.

Some of the widest use of exotics has been in the tropics and subtropics. This includes planting the tropical pines from Central America and the West Indies, most notably Caribbean pine, throughout tropical regions in the world. Exotic hardwoods, especially species of teak, acacia, eucalyptus, and gmelina have also been commonly used. Among the hundreds of species of eucalyptus are ones that are adapted to all kinds of climates from the tropical to warm temperate latitudes.

Exotics can be very successful because they have left their pests behind. This can be advantageous for a period, but it can be counterbalanced by the fact that the natural pathogens and predators of pests are also not present. When outbreaks do come from a new pest becoming adapted to the tree or an old pest being transported inadvertently from the native range, they may have a much more serious effect than in the native environment. Consequently, all phytosanitary precautions must be observed while transporting plant materials for introduction. Moving seedlings or soil is generally strictly controlled, particularly in the United States and Canada. European standards are more lax. More examples of risk are obvious in some of agriculture's most important global tree crops: rubber and oil palm. These two products are currently almost completely dependent upon plantation cultivation in Southeast Asia. Should a native disease from Brazil or West Africa secure itself in Southeast Asia, it may create a disaster for this species and industry in the region. Disinfected seeds are the most safely transported forms. However, this is problematic when attempting to translocate tropical species whose seeds often cannot endure any degree of cold or desiccating environments during transport.

Introduced species should be used cautiously until their safety and superiority have been tested in trials extending over all or most of a rotation. Only long-term tests will determine the success or failure of a particular exotic species. Even then, there can be no certainty that the most appropriate genotypes were tested. Seed must be selected from the appropriate provenance. Many failures have resulted from choosing provenances that were poorly adapted to the new climate, just as would occur in moving seed within a species' natural range. When a species has been introduced, it is wise to develop a **land race**, which is an artificial provenance adapted to the new location. This is done by letting nature take its course in the stands developed from the initial plantings, and results in the elimination of those trees that are poorly adapted to the new environment. The best of the remaining trees are then used for seed collection to establish plantations. It is important that the original plantings be derived from at least several hundred parent trees, rather than just a handful, which sometimes occurs in the very first introduction of a species into a new region.

Problems with the Use of Exotic Species

Problems with exotic species are becoming widely recognized. Plant and animal species are being moved around the world (both purposely and accidentally) at increasing rates. A small fraction of these introduced species prove to be highly adapted to the new environment and become invasive, competitively excluding native species. Hawaii is an extreme example of a place where introduced plant and animal species have become more prevalent than the native species. The potential problem to exist with an introduced plant species can be predicted to a certain extent by the "weediness" of its ability to reproduce. Plants that invade disturbed sites or reproduce clonally are likely to cause the worst problems. Herbaceous species with short generation times will

be more problematic than trees. However, the trees usually chosen for plantation silviculture are shade-intolerant species that colonize disturbed and open sites, making them potentially future problems. In a number of cases throughout the world, trees that were introduced in part for reforestation or timber production purposes have become the focus of eradication efforts. Such problems appear to be greatest in tropical and subtropical areas. In the US, some of the most damaging invasive trees are tropical ash and silk-oak in Hawaii, and melaleuca in Florida. Hughes (1994) has outlined procedures to reduce the risk of introducing species that may become invasive pests. The most obvious and important of these procedures is to minimize the use of exotics.

Particularly in the tropics, some foresters have the temptation to plant their favorite species everywhere they move from one region to another. Species trials established in one location in the tropics have tended to look very similar to those established elsewhere, concentrating on the same set of eucalyptus, teak, gmelina, and pine species. Most native species are excluded from use simply because little knowledge concerning their growth characteristics exists. New interest has arisen in establishing native species trials for use in plantation forestry. Some native species even appear to out-perform the favored exotics (Butterfield and Fisher, 1994; Hughes, 1994; Wishnie *et al*., 2007; Van Breugel, 2011).

Some of the strongest public opposition to exotics in forestry is against the planting of tropical eucalypts. This practice has received such a long list of charges against it that a worldwide review of such problems was conducted sometime ago at the height of this controversy (Poore and Fries, 1985). The alleged problems include excessive water use in semi-arid areas that reduces levels available for other uses, erosion problems, depletion of soil nutrient levels, and providing poor wildlife habitat. This has recently become a debate in the southern US, with the planting of frost-hardy eucalypts for biomass production. However, many of these problems do not appear to be related to eucalypts in particular or to its status as an exotic. Rather, they result from the use of short-rotation plantation monocultures of a highly productive species with dense roots, which take up a significant amount of water and nutrients, and eliminate understory vegetation by competition. These same conditions may occur if the species involved were a vigorous native species used in this fashion. This does not make the problems any less serious where they occur, but it is useful to separate effects that arise from the use of exotics from those that may occur in general with intensive plantation silviculture. Thus, the problem lies in poor selection of an appropriate species for the multiple social values and considerations of the circumstance at hand.

Genetic Improvement

Choices of species are also choices of genetic material made on a larger scale. In prior sections of this chapter, species' choice and selection has been passive. It has involved finding and using the best populations already available through nature, and leaving it at that, but it is possible to do better. For thousands of years, people have selected desirable characteristics for their use, particularly in agriculture and horticulture. People have used their knowledge of plant heredity to actively intervene in the processes by which trees pass their characteristics to their offspring. Zobel and Talbert (1984) and White, Adams, and Neale (2007) describe the techniques of forest genetics and tree improvement in detail.

Most tree improvement depends on finding trees with desirable characteristics and testing their progeny to determine whether the good characteristics are transmitted by sexual reproduction. Progeny do not always resemble their parents. In fact, so many combinations are possible that, except for identical twins from single seeds, no two products of sexual reproduction are genetically the same.

From the genetic standpoint, the best that can be said of an outstandingly good tree found in a wild population, is that it is a good **phenotype**. This means that the interaction of its genetic constitution and its environment has produced a tree with desirable anatomical and physiological attributes. To separate these two interacting factors, the sexually or vegetatively reproduced progeny of trees of good phenotypes are grown in uniform environmental soil conditions, and are carefully spaced to provide the same available growth resources of water, nutrients, and light. Such plantings are called **common gardens**, and demonstrate those plants displaying characteristics deemed superior to others for whatever purpose (Fig. 14.2a). This allows for more of a careful and focused selection of seed from parents with desirable **genotypes**. A statistic used in breeding called **heritability** provides an estimate of how much of the genetic diversity within a phenotype is due to genetic differences as compared to environmental.

The opportunities for genetic improvement of a species depend on the degree of genetic variability in the wild populations. If the variability is large, there are more genotypes from which to choose, so the possibility of genetic gain is large. However, high variability is also likely to mean that each individual is strongly **heterozygous**, and may thus transmit mixtures of good and bad characteristics to its progeny. Trees have not been subjected to the same centuries of human selection that have produced strains of agricultural crops that are genetically uniform or **homozygous**. Examples are the truly ancient selection of some crop plants such as corn in North America and rice in Asia. Tree breeding is quite

(a)

(b) (c)

Figure 14.2 **(a)** A common garden on Vancouver Island, British Columbia, demonstrating growth differences for Douglas-fir. The plantings in the background show trees from Vancouver Island (left back), the Rocky Mountain region of Montana (middle back), the Cascade region of northern Washington State (right back). In the foreground are new plantings of Douglas-fir. **(b)** A full-sib cross-pollination in a Douglas-fir common garden where the bags protect pollinated female cone from unwanted pollen from non-target trees. **(c)** A seed orchard of longleaf pine in the southern US coastal plain of the Gulf.

(Continued)

(d)

Figure 14.2 (Continued) **(d)** A clonal orchard of western redcedar for a source of vegetative cuttings. *Source:* **(a–d)** Mark S. Ashton.

different from that of agricultural crops, especially as compared to herbaceous annuals. Some widely recognized risks are inherent in creating crops that are genetically very uniform. The most immediate danger is that an insect or a disease may infect agricultural fields, where all the crop plants are equally vulnerable because they are genetically the same. This problem can be dealt with by having each field contain genetically uniform plants of a species, but mixing genotypes from field to field on the landscape scale. It is also possible to alternate genotypes from year to year. Uniformity within a field is advantageous for timing the many treatments (as in the case of combatting cereal rusts) and the final harvest in agriculture. In contrast, trees must live for many years, and through various waves of insects and diseases, pollutants, and climatic extremes. It is wise to maintain genetic variability of a species within each stand to ensure that all trees of a species are not equally susceptible to such effects. Going one step further would be to select multiple species for cultivation within a stand. This may be an important strategy in certain tropical climates where increased risk of year-round exposure to pathogens and insects is greatest (Kelty, 2006). Furthermore, stands of trees, unlike those of most crops of agricultural annuals, start with many more individuals than are present in the final crop. A small number of the fastest growing trees will endure natural or artificial thinnings. If the trees in a stand are too similar, especially in their rate of height growth, too many will survive and can stagnate in diameter growth. Thus there are important reasons besides reducing risk to try to maintain some degree of genetic variability.

Procedures in Tree-Improvement Programs

There are many steps in developing an advanced tree-improvement program. It is important to recognize that a forester can decide at what step and place to stop in the investment of time, labor, and money. In many circumstances, just the simple first step of securing a seed source is enough for a reforestation or restoration program. However, in a large commercial enterprise, a much larger and more expensive effort can be made for greater rewards in yield, form, and any other characteristics that are desired.

The first step in most tree improvement efforts is **mass selection** (also referred to as "plus-tree selection"), where promising phenotypes are identified from the wild population. Immediate use of this selection process can be made by harvesting seed from the selected parent

trees from the wild stands. These stands can be thinned to leave only those trees with good phenotypes, thus increasing the probability that seed collected in the stand will be from parents of good genetic stock. These **seed-production areas** also have larger crops of seeds because of the thinning. However, relying solely on phenotype as an indicator provides only a modest genetic gain, especially for growth rate. Mass selection avoids the degradation of genetic quality of seed used for planting, which occurs when seeds are collected from short, branchy, easily climbed trees. This method of seed collection was used in the early days of European forestry, and is likely the reason why many current Scots pine plantations are full of crooked trees.

The next step involves testing the offspring of the chosen trees from wild populations. The seedlings are grown in common gardens to assess the degree to which the desirable characteristics are hereditary. The seeds from each parent tree are kept separate and sown in a replicated experiment called a **progeny test**. The trees arising from each female parent are referred to as a family, so this level of selection is called **family selection**. "Open-pollinated" families of progeny are defined whereby each member shares the known female parent, but the pollen parent is unknown and may be different for different progeny in the family. These are sometimes also referred to as "half-sib" families (i.e., half-siblings). This term is technically only correct if each of the progeny is known to have a different male parent. Controlled pollination methods can also be used to produce seed in which both parents are known. This requires collecting pollen and applying it to flowers that have to be covered to prevent wild pollination. This is costly, and not widely used at this stage of selection (Fig. 14.2b). Knowing both parents would be defined as "closed pollination" and will produce progeny for evaluation in common gardens as "full-sib" families. In either case, family selection provides greater gains in desired characteristics of a tree than mass selection, because desirable parent trees are chosen on the basis of genotypes by observing phenotypes of trees of known parentage that are grown in uniform conditions.

The results of progeny tests can be used to return to the wild stands or seed-production areas, and eliminate those trees whose progeny had undesirable traits. However, if progeny tests are done, then the next logical step is to create a **seed orchard** (Fig. 14.2c). Cuttings are taken from the desirable parent trees, grafted onto root stocks, and planted in areas that are isolated from sources of contaminating pollen. Trees of the same genotype are separated to enhance cross-pollination. Results of the initial progeny tests can be used to identify families with unsatisfactory genotypes. The parent trees of such families are eliminated ("rogued") from the orchard. To maintain a large and variable gene pool in the progeny, it is desirable to start with enough trees to have at least a dozen genotypes represented in each orchard unit after roguing has been completed. Tree seed orchards can be treated much like fruit orchards. The trees are widely spaced with large crowns, and are applied with fertilizer, insecticides, and fungicides. The trees will not resemble tall, straight, forest-grown trees because they are grown in the open, but this does not affect the genetic constitution of their progeny.

The production seed orchards described above are "first-generation" orchards. The trees in the orchard come from the original mass selection from the wild trees. Progeny testing usually continues while the orchard is in production. This is the stage when making selections based on full-sib families is useful and more efficiently conducted, because controlled pollination can be carried out among trees in the seed orchard. Through full-sib family progeny tests, it is possible to identify parent trees that produce offspring with particularly desirable characteristics.

Selection procedures for tree improvement are even more complex than they sound. Selecting desirable genetic characteristics of individual trees from large populations is laborious and costly. This makes it expeditious for different workers and entities to share genetic material in an organized format. Examples include the regional breeding cooperatives between universities in the US south and the forest industry. Sharing helps develop the combinations of diversity coupled with good hereditary characteristics needed in the progeny. Tree-improvement programs are usually continuing operations that switch from one approach to another and back, or use different methods simultaneously (see conceptual diagram in Fig. 14.3). Regulated sexual reproduction aimed at seeking genetic gains may alternate with vegetative reproduction to preserve the gains that have been made. Such vegetative plantings have been termed **clonal orchards** (Fig. 14.2d). The use of rooted or grafted cuttings often speeds up progress at certain stages of the effort, but these techniques must be perfected for each species. Progress is slowed if cuttings do not root, or are incompatible with the rootstocks on which they are grafted. As testing progresses, many of the genotypes that were the best in the initial stages may be replaced either by new ones or by superior ones derived from their progeny. Usually, swiftest improvement comes when selection is made for only one or two characteristics.

Many species throughout the world have undergone mass selection to develop seed production areas. First-generation seed orchards exist for a more limited number of species. For relatively few species used in large-scale plantation silviculture, trees that are the progeny of mass selection have themselves been rigorously selected for desirable traits and combined in second-generation seed orchards. For a select group of timber trees, the process will continue to produce even more advanced generations (e.g., Douglas-fir, Monterey pine, loblolly pine, slash pine).

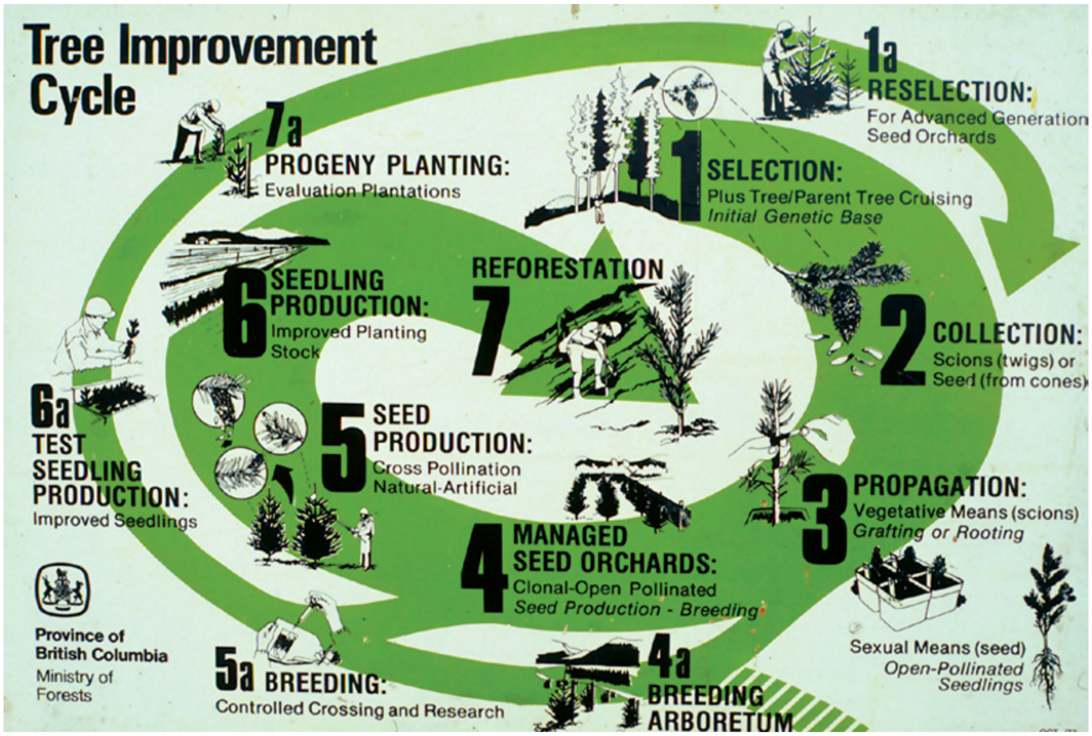

Figure 14.3 A diagram depicting the British Columbia Ministry of Forests' strategic approach to tree improvement for their reforestation program. This is an old depiction (circa 1995) but it portrays an approach that has not changed dramatically since systematic tree improvement began in the 1940s. *Source:* Mark S. Ashton.

Hybrids

Tree-improvement programs have, in a few cases, been based on interspecific hybridization. Most tree species are sufficiently far apart in their heredity or flowering phenology that they do not easily cross. However, pairs or groups of species that naturally hybridize within a genus exist among pines, spruces, larches, oaks, poplars, willows, and eucalypts. Trees arising from some of these crosses exhibit **hybrid vigor**, where the hybrid has superior growth characteristics compared to either parent. For example, loblolly–shortleaf hybrids have become a concern in the south central region of the US because they sprout like shortleaf but grow like loblolly and the natural loblolly are being replaced. However, this appears to be the exception rather than the rule.

Some hybrids prove to be practical because the crosses can be made merely by planting the different species together. A good example of this is the vigorous Dunkeld hybrid of Japanese and European larch. It becomes very laborious to produce artificial hybrids of species that only cross as a result of controlled pollination. In many cases, this process must be used with the parent species to produce each hybrid seed, because hybrid offspring does not produce viable seed. Many hybrids are infertile, and even for those that do produce seed, the resulting offspring is generally too variable in genotype to be used as planting stock. The only artificially cross-pollinated hybrid in mass production combines the straighter form of loblolly pine with the winter hardiness of pitch pine. This hybrid has proven highly successful in plantations in Korea, where they use controlled pollination for seed production. In the 1970s this hybrid was also being tested for use north of the natural range of loblolly pine. This may prove useful with climate change.

The problems of producing hybrid planting stock decrease when superior crosses can be perpetuated through vegetative propagation. This is possible with the vigorous hybrids of poplar species because their cuttings root very easily. Hybrid poplar and eucalyptus plantations from cuttings have been established for fiber production in many parts of the world.

Vegetation Multiplication and Tissue Culture

One of the impediments to implementing genetic improvement is the cost of multiplying the desirable progeny. Seeds produced from tree-improvement programs are very costly unless they come from species such as birches and eucalypts that produce vast quantities of very small seeds. Thus, the seedlings must generally be reared in nurseries and planted simply to achieve high survival in the use of the expensive seed. For some species, rooted cuttings can be used to establish plantations. This ensures the duplication of the parent tree's genotype, but has only been developed for willows, poplars, sugi (*Cryptomeria*

japonica), and some eucalypt species (Zobel and Talbert, 1984; White, Adams, and Neale, 2007).

It would be especially useful for silviculture to develop techniques for propagating whole plants vegetatively from culturing small bits of tissue in nutrient media *in vitro* (George, 1996; George, Hall, and deKlerk, 2008). Breeding programs that must rely on the sexual regeneration of tree species, which are characteristically heterozygous and slow to bear seeds, can take a long time to produce results. It can be frustrating if some desirable genotype that is the result of a rare combination of genes is not likely to be produced again. If such a genotype can be multiplied by mass-production tissue culture, many breeding problems that arise from cross-pollination can be bypassed. However, this kind of tissue culture, though now more advanced than in the 1960s, is still difficult for many tree species, and seedlings produced by it are not likely to be cheap. It is significant, nevertheless, that most varieties of woody plants used as ornamentals and for fruit production are vegetatively propagated, commonly from aberrant seedlings detected by observant growers. Tissue culture relies upon a process called **somatic embryogenesis**. This is where a cloned plant originates from a single or group of cells that are from the vegetative portions of the donor plant. Interestingly the somatic embryo that develops has no seed coat or endosperm like true seeds. Apart from the obvious application of producing genetically identical clonal plants, this technology can be used to genetically transform parts or whole plants, and to develop a variety of synthetic seed technology. Cells taken from the donor plant can be cultured to form an undifferentiated mass of cells called callus. Plant-growth regulators called auxins (see Chapter 15) are added to the culture medium and manipulated to promote callus formation; this then can be transformed into embryos using further auxin manipulation. The ratio of different plant-growth regulators required to induce callus or embryo formation varies with the type of plant.

Use of Genetic Improvement

If stands are to be established by planting, the best genetic material available should be used. Conversely, improved material can be a reason to regenerate stands by planting rather than by natural regeneration.

Genetic improvement of forest trees has not produced either the spectacular gains or the worrisome overreliance on intensive cultural practices associated with improved strains of agricultural crops. Most genetic manipulations in agriculture have been aimed at diverting more of a fixed amount of plant production into fruits, seeds, roots, or other plant parts that are most useful to humans (Silen, 1982). Total production has increased, often immensely, mainly by improving the site with fertilization, irrigation, or by controlling weeds and other pests. However, it has also been accomplished to some extent by breeding varieties that not only can take advantage of intensive silvicultural measures but are also heavily dependent on them.

Perennial woody plants are somewhat different. Most of the tree's biomass production is in the stem. This is the very organ that is usually considered wasteful in agriculture and is "robbed" to increase growth in other areas. In a certain sense, this may mean that trees are hard to improve because nature has already done much of the work. However, much effort in forest genetics has been spent on increasing biomass productivity per acre. Because of the variable effects of site conditions on production, it is very difficult to determine whether this objective has been or can be achieved. The growth rates of individual trees have definitely increased, but these do not expand productivity per unit of land area unless trees of given size occupy less growing space because of their more efficient use of growing space. Much confusion and heightened expectations have come from projecting percentage gains in individual tree height and volume that are achieved in young trees in small plots in order to predict gains for operational plantations. More rigorous testing is needed to assess the realized productivity gains from tree improvement. In the last 20 years, some of this testing has come to fruition in the south with loblolly pine (Jokela, Dougherty, and Martin, 2004).

It is worth noting that if individual trees grow faster, they may attain optimum sizes on shortened rotations even if the production per unit area does not increase. Since different species clearly differ in production levels per acre, it seems likely that similar differences must exist within species (Cannell and Last, 1976; White, Adams, and Neale, 2007). Much of the evidence suggests that the faster-growing trees are those adapted to favorable sites or parts of their natural range. As long as the growing conditions remain favorable, artificially or naturally, these faster-growing varieties can persist on sites where they might ordinarily suffer damage from drought, cold, or similar problems. In other words, increases in forest production may come with similar costs to improvement in agriculture.

Tree-improvement work is focused on important factors other than trying to increase productivity. Some of the greatest gains include stem form, branching characteristics, resistance to insects and diseases, wood density, fiber length, and resin production (White, Adams, and Neale, 2007). There is evidence that success comes most rapidly with artificial selection for characteristics, such as stem quality or wood density, that appear to have little importance for survival as a species. In such cases, traits that are both good and bad from the human standpoint are very likely to have persisted in natural populations for no apparent reason, but this can be debated.

Genetically modified organisms (GMOs) can be defined as organisms in which the genetic material (DNA) has been altered in a way that does not occur naturally by mating and/or natural recombination. Genetically modified trees (GMTs), similarly, are trees whose DNA has been purposely engineered by introducing traits which do not necessarily occur naturally within the tree species population at large. Such DNA traits have been taken from other plants and organisms mainly to create resistance to insects and diseases, increasing tolerance to frost, or to improve herbicide tolerance. Work on GMOs for forestry is considerably behind that for agricultural crops (Barker *et al.*, 2013). In the US, most work on GMTs is being done by the pulp and paper industry to increase the disease resistance and frost tolerance of fast-growing trees with low lignin (e.g., hybrid poplar, eucalyptus) (Fig. 14.4). Work is also being done on the American chestnut. In Brazil and China, trials on eucalyptus and poplar respectively, have been progressing in the same manner as in the US. In the US, GMTs have not been approved yet; in China poplar has been approved, and in Brazil eucalyptus has been approved. The Convention of Biodiversity has taken a very conservative stance given the potential high environmental costs of pollination pollution by GMTs with the native tree populations (Strauss *et al.*, 2009). A likely precondition is ensuring GMTs are sterile. GMTs that have been deregulated in the US are in the fruit orchard industry, and include papaya and plum (Barker *et al.*, 2013).

Conservation of Genetic Resources

Maintaining genetic variation is vital to the long-term survival of any species. It is the raw tree material that breeders work with to develop more useful genotypes for various objectives. Many organizations maintain “clone banks” to keep genetic material for as long as possible. The goal of tree improvement is to narrow the genetic base with respect to the important characteristics being selected for, while maintaining the variability that exists for characteristics that affect general adaptability. This can be done by breeding for the same desirable traits (e.g., straight stems or greater wood density) simultaneously in a series of different populations (Namkoong, Barnes, and Burley, 1980; Zobel and Talbert, 1984; White, Adams, and Neale, 2007). In some cases where intensive tree breeding has produced improved seed that is used on a wide scale, depletion of the genetic base may occur, if these or other efforts at maintaining variability have not been followed. However, this is generally more of a risk for the landowner of such plantations than for the species as a whole. Plenty of wild populations usually still exist. The risk for landowners is greatest when using clonal reproduction, such as with poplars. It is important to maintain at least a dozen or more clones or families within each planting area in order to reduce the risk of losing genetic variability at the stand level (White, Adams, and Neale, 2007).

The dangers to the genetic base of entire species do not come from tree-improvement programs, but rather from the various forces that underlie the conversion of large areas of forest to agricultural fields, pastures, or degraded woodlands from firewood harvesting. High-grading or diameter-limit cutting of stands can also be more damaging to genetic resources because the best genotypes and species can be removed from a stand (Ledig, 1992).

Most threats to tree genetic resources are not of species’ extinctions, but of loss or reduction of varieties or races that decrease the genetic base to a fraction of its original level (Ledig, 1992). Natural populations of trees are an immense storehouse of hidden genetic resources. It is increasingly obvious that significant samples of truly natural forests must be maintained or allowed to regenerate. This is necessary to maintain potentially important gene combinations as part of a strategy to preserve biodiversity of all kinds of plants and animals. Such places are also sites where foresters can truly learn about the natural developmental processes that they claim to be able to direct. In some cases, it is advantageous to supplement these large nature reserves with small stands scattered across the range of a species, principally for the purpose of tree genetics conservation. In contrast to wildlife conservation areas, such stands only need to be a few acres, because a genetically diverse population of trees can be maintained in a small area. Seed can be used from these areas to incorporate into breeding programs. Regeneration within the conservation areas is strictly from the mature trees of the stand without artificial selection. A series of gene-conservation stands has been established for various species across their native ranges. They have also been created for exotic pine species in South Africa by planting small stands with no artificial selection in areas where large plantations of improved pines are being established. In the case of a number of tropical pine species in Central America, widespread forest clearing creates a real danger of losing entire species (Ledig, 1992). Cooperative efforts are underway to plant conservation areas with these species.

Other methods, such as grafted clone banks or long-term seed or pollen storage using freeze-drying techniques, may be used in the future. These methods will likely be developed for agricultural crops first. The entire range of alternatives for conserving forest genetic resources has been reviewed by the National Research Council (1991).

Genetic Improvement with Natural Regeneration

The principles of genetic manipulation of trees are usually used to improve planting stock. However, choices that are made regarding which trees to cut and which to

(a)

(b)

Figure 14.4 Trial plantations of genetically modified trees. **(a)** In Brazil with eucalyptus. *Source:* P. Vilela. Reproduced with permission from Shutterstock. **(b)** In China with poplar. *Source:* Lorenzobi. Reproduced with permission from Shutterstock.

leave during partial cuttings can affect the genetic quality of the progeny arising from natural regeneration. Thinnings, seed-tree cuttings, and shelterwood cuttings are selections made among trees based on multiple phenotypic characteristics, which are similar to those made in mass selection for seed collection (Wilusz and Giertych, 1974; Bassman and Fins, 1988). Leaving the best phenotypes at each stage will increase the probability that seedfall in the stand will come from genetically superior trees. The selection intensity is generally not as

great in a series of thinnings and regeneration cuttings as it is in mass selection for seed collection (i.e., a larger proportion of the population contributes to the seed production with natural regeneration), so genetic gain is not expected to be as great. Similar to intensive breeding programs, improvement is likely to be greater for stem form and pest resistance than for growth rate.

It is perhaps most important that foresters recognize that poor judgment in tree selection during stand tending can lead to genetic degradation in naturally regenerated stands. These effects may not be apparent after one cycle of high-grading because enough high-quality trees will exist to produce a new stand. However, successive rotations of this kind of treatment will seriously diminish the genetic potential of future regeneration cycles (Zobel and Talbert, 1984). Even if genetic gains are not achieved in natural stand management, simply preserving the level of genetic quality and variation of the original stand is a worthwhile goal. Maintaining genetic quality is second in importance only to maintaining site quality when sustaining the long-term productivity of managed forest stands.

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15

Nursery, Planting, and Seeding Techniques

Introduction

The best way of establishing trees is to rear them in a protected environment and then plant them where they are to grow. This way, they are not exposed to the rigors of the site until they have successfully passed the most critical early stages of growth. Many of the microenvironmental problems that were discussed in Chapter 5 on the ecology of regeneration are simply bypassed by using the planting method. The planted trees can be from **wildlings** of natural origin, dug from elsewhere in the forest. However, it is usually more efficient to raise planting stock in nurseries or greenhouses. The plants can be either rooted or non-rooted cuttings, or seedlings. However, what appears simple and straightforward is in fact rather complex. When working with a "natural regeneration method," the knowledge of seed collection, storage, propagation, and then planting, is substituted for what nature ordinarily does. It is important to carefully consider whether or not propagation and planting is the right choice, particularly when our knowledge of the ecology of regeneration is incomplete. Propagating and planting to grow a new forest or tree should not be taken lightly. Plenty of costly failures exist where people and governments have made grand proclamations about planting, only to end in a fiasco.

There are two basic circumstances to consider when thinking about planting. First, planting is necessary to ensure a particular composition and structure. This usually means that the landowner wants to grow trees that have a sufficiently high value, either as a service (shade, aesthetics) or as a commercial product (food, timber, fiber) for which the control over the investment is important. Examples in commercial forestry would be high production timber or an intensive biofuel operation. Examples in urban forestry would be a street tree for shade or aesthetics. In agroforestry, it would be as a nurse crop for nitrogen fixation and crop shade, or for fruit, nut, or latex production.

The second circumstance is if the nearby seed sources or dispersal agents for natural regeneration have been lost, or if the sites that you wish to regenerate are sufficiently inhospitable that seed will not germinate. Then you have no alternative but to plant. This occurs in circumstances that relate to watershed and soil stabilization from erosion and desertification, and for reforestation of open lands that are devoid of trees for creation of wildlife habitat.

This chapter covers all of the most important factors necessary for successfully planting trees. The first part deals with the collection, cleaning, and storage of seed, and then the germination of seed and the propagation of seedling and vegetative stock within a nursery. Three major propagation techniques are discussed: (1) **bare root**, (2) **containerization**, and (3) **vegetative**. The second part of this chapter discusses the transportation and planting of bare root seedlings and containerized seedlings in the field under different circumstances. The chapter concludes with the use of broadcast seeding and spot seeding.

The major sources of information on plant propagation can be read in the comprehensive textbooks and manuals by Young and Young (1992), Hartmann *et al.* (2001), and Dirr and Heuser (2009). Among the sources of detailed information for planting and on continuing developments in artificial regeneration is the journal *New Forests*. There are also comprehensive accounts by Shepherd (1986), Lavender *et al.* (1990), and Evans and Turnbull (2004), on the establishment of plantations.

Propagation

Collection

In most circumstances, seed is provided to nurseries for propagation by professional seed growers. Seed from the original propagator of the variety desired for cultivation is called the **breeder's seed**. Seed derived from plants in other nurseries that obtained seed from the original breeder is called **foundation seed**. The seed that nurseries sell to the public for farmers or tree companies to use for general cultivation, is called **certified seed** and usually means that their pedigree can be traced back to the original breeder. This is a common protocol

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

for the horticulture and agriculture business where varieties of particular species and their desired genotypes can be very important. This can be important in forestry where trees are planted in agricultural and urban settings. Most nurseries for forestry operations generally order seed from state and private seed orchards or clonal orchards (see Chapter 14).

In situations where wild seed has to be collected for propagation, it is important to have previously identified seed-production areas (see Chapter 14). Harvesting seed needs to be done with a good understanding of the species' fruiting age (reproductive maturity), the nature of species phenology (when seeds ripen in relation to season), the mode of dispersal (wind, water, bird, primate), and the amount of seed produced. Knowing which individual trees are reproductively mature (especially in dioecious species), and at what age and size, allows one to plan accordingly as to how to collect the seed. Collecting seeds at the right time is critical. It is best to collect the seed or fruit directly off the tree before it falls to the ground and is eaten by insects and animals or becomes susceptible to pathogens. For seeds dispersed by animals, it is best to take fruits just before they turn color (reds and purples are bird dispersed) or become pungent (bats, primates).

Seed collection itself is done in all sorts of ways from using bucket trucks or ladders to access the tree's canopy, climbing the tree, or by using pole shears. In seed orchards, one approach is to lay fine cloth around the base of the tree and then mechanically shake the bole to drop fruits and seeds.

Collecting wildlings is the best approach where seeds are very difficult to collect because it is impossible to access the canopy, or because the fruiting is irregular and occasional. This is common in many tropical forest environments (Weirsum, 1997).

The best practices for the collection or any treatment of tree seeds vary widely with species. It is always desirable to consult sources such as manuals of the seeds of woody plants for the treatment details and quantitative data about the seed of various species (Bonner and Karrfalt, 2008; Young and Young, 1992).

Seed Preparation

After the seeds or the fruits containing the seeds have been collected, some species do not have to be cleaned. For the seeds that do need cleaning, the nature of the cleaning depends upon the type of fruit and seed. Cleaning can be categorized by three types of treatments: (1) dry seeds, (2) dry fruits, and (3) fleshy fruits. Most trees that produce dry seeds are within fruits that dehisce readily at maturity, such as capsules (e.g., mahogany), pods (e.g., legumes), and cones (e.g., conifers). Dry seeds can be left in fruits to open in the sun. This process can be sped up by placing the fruits in drying ovens and then tumbling them. When open, many of these seeds have wings because they are dispersed by wind. For storage purposes, wings can be broken off either manually or by machine. Dry fruits characteristically have a unified fruit and seed where the fruit is the outer covering of the seed, such as in grains. Many species have dry fruits with appendages, such as hairs and wings. To increase seed purity for storage, the extraction treatment involves threshing and blowing to remove the chaff (e.g., grains: wheat, barley, oats, rice). Fleshy fruits are those in which seeds are embedded within a pulpy covering (e.g., berries, drupes, and compound fruits). The fruits are crushed and macerated into a liquid, and then the seeds are filtered and washed to prevent mold.

Storage

Once the seeds have been cleaned, storage is the next concern. The factors that can be controlled are the ones that relate to how seeds are stored in the natural environment: temperature controls that simulate winter, moisture controls that simulate the dry season, light control to simulate disturbance or understory closed canopy conditions, carbon dioxide and oxygen levels, and gases that regulate seed respiration and activity. Seeds from different climates and successional guilds require different combinations of these factors. For example, large seeds such as nuts (e.g., acorns) are usually associated with late-successional trees from moist temperate or tropical regions (see Chapter 5). The seeds, being large, are prone to desiccation. The most appropriate way to store such species from temperate climates is to simulate a cool wet winter by storing seeds above freezing in a refrigerator in a moist medium, such as sand. However, it is important to recognize that these large seeds, such as from oaks or walnuts, are difficult to store past the time when they would normally germinate, in the first spring. If these species evolved in a tropical environment they would likely germinate immediately, like so many other tropical large-seeded species.

Tree species from the boreal region have smaller seeds that can be stored in dry frozen conditions, by placing them in desiccant bags in a freezer. Many of these boreal species can be stored in the dark for many years. Seeds from Mediterranean, desert, and dry tropical climates are usually small with hard seed coats. These can usually be stored at room temperature within packets that control humidity (Table 15.1). Finally, there are many tree species, especially from the moist tropics, that cannot be stored because their seed germinates almost immediately upon ripening. The term for immediate germination is **recalcitrant**. These species are the most obvious form of advance regeneration where they store themselves as seedlings in the understory, waiting for release

Table 15.1 The factors to control, and methods of storing seeds.

Factors to control	Methods of storage
Open storage	Room temperature of stored seeds. The natural humidity in the air does not need to be controlled. Many grains can be stored in this manner
Control of water	Storing seeds at room temperature but within watertight containers that maintain a low humidity environment is reflective of annuals from seasonally dry climates (Mediterranean and dry tropical climates)
Control of temperature in moist conditions	Many large-seeded species from temperate moist climates need seeds to be stored in a way that mimics winter. Seeds are desiccation prone and need to be embedded in moist sand at cool temperatures (just above freezing) within a refrigerator. Most seeds cannot be stored indefinitely in this condition
Control of temperature and water	Many seeds from boreal climates require below freezing conditions that are desiccating. Most of these species are small seeded and cold tolerant. Keep seeds in desiccated air-tight containers within a freezer. Seeds can be stored for multiple years in this condition
Seeds that germinate immediately (recalcitrance)	Many ever-wet tropical and temperate rainforest species cannot be stored, but germinate immediately and remain as seedlings within nurseries, where their growth is retarded by providing shade. These species would be considered as advance regeneration in forest understories

Source: Mark S. Ashton.

from a canopy disturbance. They are best collected as wildlings and are then stored as seedlings under deep shade, which simulates their advance-regeneration environment (Shono, Cadaweng, and Durst, 2007).

Since so many of the most commercial conifer species are within the same guild and include similar seed autecologies, they can be treated the same. Most can be stored for periods of 3–10 years and sometimes longer, if held at low temperature and low moisture content in sealed containers. The proper moisture content varies from 4–12%, depending on the species. The temperatures should be below 41 °F (5 °C), preferably in the range from 64 °F (18 °C) to 32 °F (0 °C) and colder, with southern pine seed stored at 10 °F (-12 °C). It is important to dry the seeds uniformly and to prevent fluctuations in moisture content during storage. Under these conditions, respiration continues at the level necessary to keep the embryos alive. Only small amounts of the stored carbohydrates are converted into carbon dioxide in the process. Polyethylene bags make good containers because they are impermeable to water, but less so to oxygen and carbon dioxide. These attributes prevent changes in moisture content but allow slow exchange of the gases involved in respiration to continue through the container walls.

Germination

Dormancy

Seed in storage that is ready to be germinated often needs to break dormancy. The two major kinds are: (1) dormancy that is promoted by the seed coat on the outside of the seed itself (**external dormancy**); and (2) dormancy that is promoted within the seed (**internal dormancy**) (Finch-Savage and Leubner-Metzger, 2006; Vleeshouwers, Bouwmeester, and Karssen, 2007).

Dormancy Promoted by the Seed Coat

Species from Mediterranean, desert, and dry tropical regions have hard seed covers to retain moisture and avoid desiccation. These species need to have their seed coats scratched or washed in acid to partially dissolve the coat. The process is called **mechanical scarification** and simulates the abrasions that gravel makes against the seed coat at the onset of the rains. The abrasions allow water to move into the seed and start the process of germination. Some plant species from the same kind of climate have seed with chemicals on the seed coat to inhibit germination until washed off by rain. Washing off the chemical in a tumbler is defined as **chemical scarification**. Also bird-dispersed species often require the pulp to be macerated off the seed coat. The seed coat then needs to be scratched to imitate the bird's crop before it is passed out of the gut. The pulp often has a chemical that inhibits germination. Chemical or mechanical scarification can be used to replicate this.

Dormancy Promoted within the Seed

Seeds that remain dormant internally are triggered by environmental variables related to season. It is a condition within the seed ordinarily resulting from incomplete digestion of the fats, proteins, and other complex insoluble substances stored in the seed. Before germination can occur, these compounds must be broken down into simpler organic substances, such as sugars and amino acids, that can be translocated to the embryo. The necessary conditions are low temperatures and/or darkness. Thus, the two main processes of breaking dormancy are through temperature (simulating winter by chilling, called **thermodormancy**) and light (shifting from a period of darkness to light, called **photodormancy**).

Many seeds of temperate and boreal climates exhibit thermodormancy. These conditions are created

by storing the seed in cool, moist substances, just as would occur in the natural forest floor. This process is called **stratification**, because it was originally done by putting layers of wet seeds between layers of wet sand. The enzymes that catalyze the breakdown of the complex stored substances are capable of functioning in a cool, moist environment, but those that cause the rapid respiration necessary to release energy for germination and growth of the embryo are not (Finch-Savage and Leubner-Metzger, 2006). Consequently, the stored substances eventually used by the embryo are mobilized without being converted into carbon dioxide by maintenance respiration. Stratifying seed in mixtures with wet sand or peat moss is a time-consuming procedure, and also exposes the seeds to mold. With most species, it is just as effective and much simpler to store wet seeds in polyethylene bags at 36–41 °F (2–5 °C) for 1 or 2 months.

Species associated with buried soil seed banks often require a dramatic increase in light from storage in the dark, thus simulating a period of shaded understory before a disturbance. In other species, particularly annual herbs, progressively increasing light exposure simulating increased day-length is the trigger, signifying an oncoming spring.

Other Mechanisms of Dormancy

Some species have inherently immature seeds (**rudimentary embryos**) when fruits are dispersed, and it takes time before the seeds mature and germinate. Many species that exhibit this form of delayed germination establish and grow within environments where a period of time is required for effective dispersal before germination. Examples are often related to dispersal by water (e.g., seasonal flooding of rivers or the circulation of ocean currents). The coconut, for example, has a seed with a rudimentary embryo that matures as the fruit drifts with the ocean currents, and has delayed germination, allowing it to reach a new land surface.

Kinds of Germination

Seed germination can be defined by where they germinate in relation to the soil surface and by differences in their morphology. First, seeds can be categorized by their morphology. Most important is the organization of their cotyledons. Cotyledons are appendages that are part of the seed embryo. They contain the seed's food reserves, and often act as the first seed leaves that photosynthesize upon seed germination (Fig. 15.1). Most broadleaved

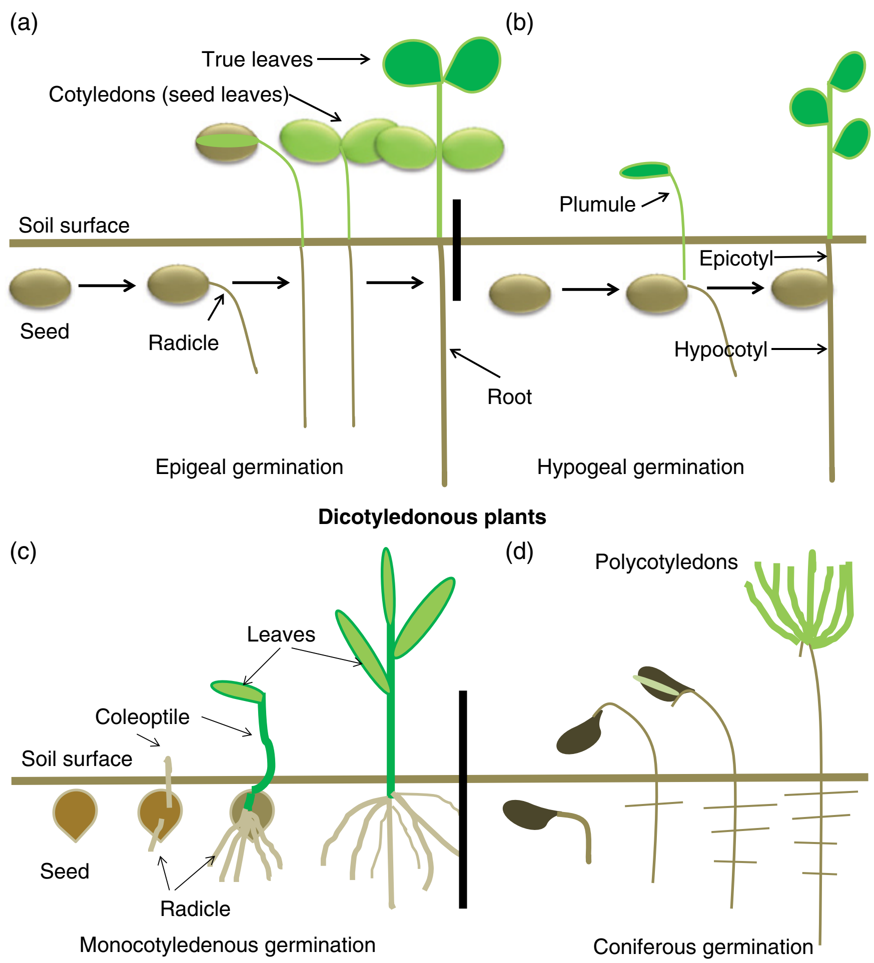


Figure 15.1 Depictions of germination and characterization of position and number of cotyledons by (a) dicotyledonous (dicots), epigeal germination; (b) dicotyledonous (dicots), hypogeal germination; (c) monocotyledonous (monocots); and (d) polycotyledonous plants (conifers). *Source:* (a–d) Mark S. Ashton.

species (angiosperms) are dicotyledonous (two cotyledons). **Dicotyledonous** species either germinate and raise their cotyledons aboveground as the seed germinates to act as the first photosynthetic organs (**epigeal**, e.g., legumes), or remain belowground (**hypogeal**, e.g., acorns). Hypogeal seeds are usually larger with greater reserves that a seedling can draw upon. Epigeal species have smaller seeds, and their cotyledons are used as an immediate site for obtaining energy and manufacturing sugar from photosynthesis. **Monocotyledons** (single cotyledons) are associated with a minority of angiosperms that are largely herbaceous (e.g., grasses, banana, palms, lilies). Conifers (gymnosperms) are **polycotyledonous** (meaning "many", from 2–24) and upon seed germination are erected above the soil surface for rudimentary photosynthesis (Bewley, 1997).

The Process of Germination

Germination starts as an invisible process to the naked eye. The first activity is the absorption of water through the seed coat, then the expansion of the cells, and then the stimulation of enzymatic activity. Several hormones stimulate enzyme activity, and others inhibit activity. **Abscisic acid** is a common hormone that promotes dormancy and slows plant growth. During germination, abscisic acid is counteracted by **cytokinins** that promote cell division. This is the most important interaction to stimulate the germination process. Other hormones, called **giberellins**, regulate cell elongation and stem growth that develops. The last group of hormones to consider are the **auxins**: indolacetic acid (IAA) and indolebutyric acid (IBA). They are present throughout the plant's growth, and regulate its organ development. For example, IAA is primarily found in the tips of the stems and young leaves. It is important in orienting the stem and leaves toward light. IBA is important and often used to stimulate rooting (Bewley, 1997).

The ability of seeds to germinate will differ dramatically between species and different environmental conditions. In the nursery industry, measures have been developed to assess germination performance (Fig. 15.2). **Germinative energy** and **germination capacity** are both used to measure the quality of seed provided and the environmental conditions in which the seed is germinating. The higher the germinative capacity and the germinative energy, the greater the viability and quality of the seed under the germination environment tested. In addition, the viability of the seed that has been gathered or bought can be assessed by several initial pre-germination measures: (1) the **cut test** dissects a sample of seed to examine a proportion of the seed to live tissue; (2) the **tetrazolium test** stains all viable seed red as a measure of respiration; and (3) x-rays can differentiate hollow from solid seeds.

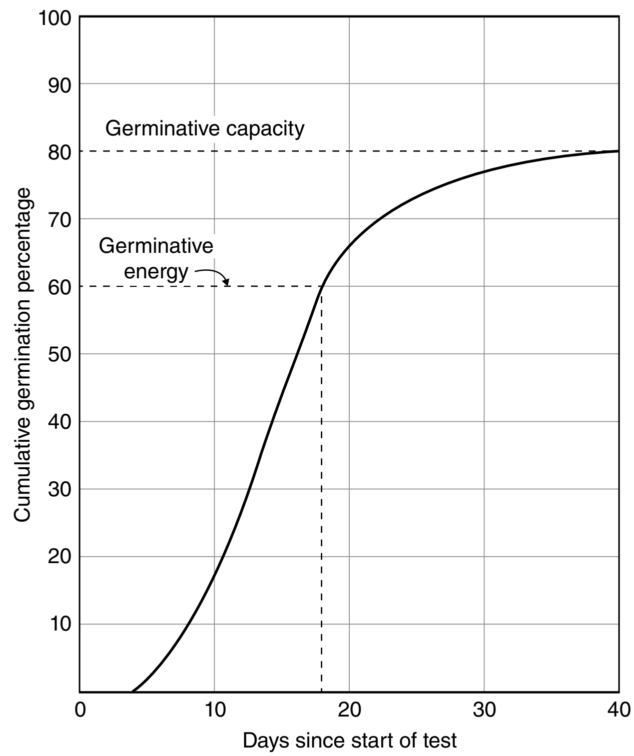


Figure 15.2 A depiction of seed germination, illustrating germinative energy as a measure of time that it takes to reach peak rate of germination and germinative capacity as a measure of maximum germination. *Source:* Yale School of Forestry and Environmental Studies.

Nursery Management

Nurseries come in all shapes and sizes. There are three major classifications: (1) bare-root nurseries, (2) containerized nurseries, and (3) vegetative propagation nurseries. Bare-root nurseries propagate seed in outdoor beds. Once they are ready, seedlings are lifted up, stripped of soil, packaged, and shipped to reforestation sites for immediate planting. Containerized nurseries germinate and propagate seeds entirely within containers of potting medium, usually within enclosed spaces that can control temperature, water, nutrition, and light, or some combination. Nurseries that specialize in vegetative propagation rely upon cloning that can be containerized or bare-root. The kind of operation and the size of a nursery will depend on the ecological, social, and economic circumstance at hand. The first thing to consider as a forester is what kind of planting stock is wanted.

Kinds of Planting Stock

The roots must go deep enough and grow fast enough to maintain contact with the soil moisture supply. As far as the top of the plant is concerned, all that is basically necessary is that it has some shoot, bud, or apical meristem capable of growing into a tree. There must also be enough

carbohydrate and other nutritional material stored in the seedling to enable it to resume growth after planting.

The most common types of planting stock are bare-rooted and containerized seedlings. **Bare-rooted seedlings** have roots that are separated from the soil they were grown in before they are taken to the ultimate planting site. Their survival after planting depends on quickly reestablishing functional contact between the roots and the soil. This problem is avoided with **containerized seedlings** or **vegetative cuttings**, which are moved to the field in the soil they were grown in, and are planted with the soil still attached to the roots. With some species, it is also possible to plant vegetative cuttings immediately on site. Cuttings are segments of stems or roots (sometimes leaves) with buds that are capable of sending out new roots.

Size of Planting Stock

There are tradeoffs between small and large seedlings. Bigger is not necessarily better. Large planting stock can be more costly to grow, harder to plant, and less likely to grow well. Many roots are unavoidably killed or broken off when bare-rooted seedlings are removed from nursery seedbeds. Growth is poor when too much root tissue has been left behind in the nursery, with the top intact. If the top of the seedling is too large compared to the roots, it transpires more water than the roots can provide. Containers restrict the sizes of root systems unless the seedlings are planted when very small and tender.

A planted tree with a large top is readily visible and looks very impressive, but it costs considerably more than seedlings. Even if it survives, it may be so slow to resume active growth that a smaller planted seedling may actually overtake it in size. One of the most important characteristics of young trees is that a large tree with a tall top has the greater likelihood that it will not be overtopped by competing vegetation. However, a tall seedling can also project above the tree strata in which damage by animals or other agencies is common. For example, in planting saplings for street trees, the tops should be taller than the level of people's eyes and the reach of children. Short seedlings are sometimes too easily buried by fallen leaves or eroding soil. Plants often have to grow to a certain size before they have enough stored carbohydrate or conductive tissue to resume development after the damage inevitably associated with planting. Deep-rooted seedlings tend to be less susceptible to frost heaving, and those with thick bark are less prone to suffer heat injury.

Many of the crucial characteristics of nursery stock, therefore, have little or nothing to do with seedling size. Physiological health, capacity for root regeneration, and similar attributes are controlled by the conditions of nursery culture, handling care, and the degree to which the timing of lifting the seedlings from the soil is synchronized with the seasonal regime of plant development.

Bare-Root Nurseries

Selecting a Site

Bare-root nurseries are inherently dependent upon selecting the absolute best location for their establishment. Good bare-root nurseries have access to water for irrigation and have labor available for periods of intensive propagation and lifting/transplanting at the beginning and end of the growing season. Also necessary is electricity for power and access to a road network to efficiently transport seedlings to planting sites. Most important are the ecological constraints. The nursery has to be located on the best soil possible for cultivation. This means seeking a site with well-drained sandy soil that is free of pathogens. And finally, in temperate or boreal climates in particular, selecting a location with the mildest subclimate within the region that the nursery is intended to serve (e.g., where water moderates the climate such as coastal or lakeside areas) can be critical to get a jump on spring operations and to extend fall activities, but not too mild to never induce dormancy.

A deep, well-drained slightly acid soil is paramount for good propagation. It prevents water-logging and pathogen buildup, and minimizes frost heave in regions sensitive to spring frosts. At the same time, soils that already contain pathogens need to be avoided, this means soils with active agriculture (Fig. 15.3a). Virgin forest soils are the best, but it is unlikely any exist in the world because most of these soils have been converted to agriculture. Selecting an old-field or second-growth forest that is now fallow, but was originally used for agriculture, is the next best thing. Many of the pathogens that were once in the soil have been lost because of the time since the host plant was cultivated. Soil sterilization is also used to remove pathogens more quickly and completely. Well-drained soils are droughty and sandy. Soil manures and organic mulches need to be applied to build the water-holding capacity and fertility. This is almost a continuous process because they decompose quickly in these well-aerated soils. This is a drawback to selecting this kind of soil, but it is secondary to water-logging and pH problems finer textured soils have.

Bare-Rooted Seedlings

The greatest advantage of bare-rooted seedlings is that no heavy, bulky soil is attached. Therefore, it is comparatively easy to transport large numbers of such seedlings to the field. It is also possible to produce and handle very large numbers of them expeditiously and comparatively cheaply in outdoor nurseries. However, reestablishing contact between roots and soil is such a crucial and

Figure 15.3 Nurseries come in all shapes and sizes to accommodate the social and ecological circumstance. (a) A bare-root nursery at the Wind River Experimental Forest on the Pinchot National Forest, Washington. (b) A containerized nursery operation at the British Colombia Ministry of Forests, Lake Cowichan Research Station. (c) A temporary containerized nursery for enrichment planting rattan into the rainforest. *Source:* (a–c) Mark S. Ashton.

fundamental problem that the planting can be done only during those short seasons when rapid root growth takes place.

Ordinarily, the seedlings are grown in the seedbeds until the root systems are extensive enough and the tops tall enough to be planted. The minimum plantable conifer seedlings measures should usually be at least 0.08 inch (2.0 mm) in **caliper** (basal diameter), 4–14 in (10–35 cm) in aboveground height, and with a top-to-root weight ratio of less than 4 to 1.

If the roots are too small for the tops or are too sparse and sprawling, the seedlings can be lifted and replanted in rows elsewhere in the nursery. In silvicuture, this step is called **transplanting**. The term "planting" is reserved for final placement. Plants produced by this method are called **transplants** to distinguish them from **seedlings**

Figure 15.4 **(a)** Transplanting 2-year-old bare-root seedling stock to a wider spacing. *Source:* T. Landis, USDA Forest Service, Bugwood.Org. Reproduced with permission from T. Landis. **(b)** Root pruning the seedling stock to encourage a fibrous root system. *Source:* T. Landis, USDA Forest Service, Bugwood.Org. Reproduced with permission from T. Landis. **(c)** Seedlings being lifted from beds to be sorted, graded, and packed for field planting. *Source:* Mark S. Ashton.

grown in the original seedbeds. Transplanting makes the root systems more compact with a larger number of fine lateral roots than found in seedlings. If the seedbeds were crowded, the operation makes the tops grow larger. The regrowth necessary for reforming the root systems occurs if the plants are left to grow in the transplant beds for a year or, less commonly, 2 years (Fig. 15.4a).

Root pruning is an expeditious substitute to transplanting (Fig. 15.4b). The objective is to make the root systems shorter but more compact. This can be done by drawing a horizontal blade under the seedling bed at an appropriate depth. **Wrenching** is a more severe form of root pruning. The horizontal blade is tilted so that the whole seedbed is lifted slightly to rupture the roots of seedlings enough to reduce their growth or induce early dormancy. The root systems can also be trimmed off at the sides with U-shaped blades if the seedlings are in drills. The seedlings are usually left to grow for another year after these treatments.

Sometimes it helps to bring the tops into better balance with the roots by mowing back the tops of the terminal shoots. If this is done when the tops are succulent and actively growing, most conifers and hardwoods will form new buds that create new tops. This treatment can also be used if the plants must unexpectedly be left in the nursery for another year and might otherwise grow too large. If the roots are longer than the anticipated depth of the planting holes, they should be pruned back enough

to facilitate planting. Because the ends of the roots are often killed by the lifting operation, root pruning may not actually sacrifice any useful tissue.

Tropical angiosperms, such as teak or Spanish-cedar, often grow very large before they become dormant at the end of the first growing season. If they are capable of sprouting, they can be trimmed down to plantable size by severely pruning both the top and roots. The stubby **stump plants** or **truncheons** that are created typically have 2 in (5 cm) tops and 6 in (15 cm) long roots.

The Working Seasons of the Year

The first concern in preparing to cultivate a crop of seedlings is to form the beds, measure the soil pH, and, if necessary, add lime to increase pH. These beds are formed after plowing under a fallow crop (often nitrogen-fixing, such as clover) that adds organic matter. Traditionally, the beds are 4 ft (1.2 m) wide, allowing manual weeding on either side, or mechanized equipment to travel over the top. Beds are raised by about 6 in (15 cm) to further improve drainage. They can be formed in the fall for the seed sowing that requires stratification (particularly relevant to temperate and boreal climates). Fall-sown seed requires netting to protect it from rodents and birds, and mulch to serve as insulation and to reduce seed emerging at the surface after frost heave. Mulches should be inert and as sterile as possible (e.g., pine needles, salt mash hay) to avoid contamination by weed seeds.

In the early spring, germination has to be closely monitored for the freeze–thaw action that can heave germinating seedlings out of the soil. Nurserymen are always vigilant for lethal cold night-time temperatures in the spring. They use water spray that freezes around the young fleshy germinants to insulate and protect them from still colder, more desiccating temperatures and winds that would kill them. Later, the mulch can be gently removed, because it can impede the germination of small-seeded species. For the shade-tolerant seed species, shade cloths are erected and maintained over the beds before the young germinants develop.

During the growing season, irrigation water can be added to avoid drought conditions to young fleshy seedlings. Fertilizer (particularly nitrogen) can be added through the irrigation system because this is a time when roots and shoots are growing vigorously. Applying nitrogen at times when seedlings are not growing is generally wasted by leaching, and the sandy soils can be an important source of pollution into nearby groundwaters. During the growing season, routine manual weeding needs to be done with seasonal labor or with herbicide use.

Toward the end of the growing season, seedlings need to be **hardened off**. Their growth needs to slow and to be reallocated to build the stem and store reserves in a larger root system. If this is not done, it can **shock** fleshy seedlings from sudden exposure to a cold snap or to a dry spell that can cause significant dieback. Hardening off seedlings also prepares them for lifting and transplanting, or for storage and transport to their planting sites. For these activities, it is preferable to treat seedlings when they are dormant. This is when roots can be pruned to increase fine root mass and soil water absorption for the next growing season. Shoots can be pruned to reduce leaf area and transpiration stress, and to reallocate carbohydrate belowground. Pruning prepares seedlings for transplanting or harvesting for out-planting. As previously mentioned, it can also regulate spacing between seedlings and avoid transplanting so as to grow for a second year in the same bed.

If seedlings are grown for a second season, they can be mechanically lifted, shaken of soil, and transplanted at a wider spacing into new beds as transplants. Most seedlings for reforestation are not grown beyond 2 years. Seedling stock that needs to be large for urban plantings can continue to be transplanted on a yearly basis at continually wider-spaced intervals until they reach the desired stock size. Though transplanting operations are usually done in the early fall to allow for acclimation, lifting of seedlings or transplants for out-planting can be done in either the fall or spring. In the fall, seedlings and transplants are placed in cold storage for the winter and are ready for planting early when the growing season starts.

Classification of Bare-Root Nursery Stock

The primary classification of bare-rooted nursery stock depends on the age and treatment of the plants. These two characteristics are designated by two figures. The first represents the number of years through which the plants grew as seedlings in the original bed, and the second represents the number of years they were grown as transplants. For example, "1-0" indicates a 1-year-old seedling that has not been transplanted; "2-1" designates a 3-year-old transplant grown 2 years as a seedling and 1 year as a transplant. Similar letters and numbers are used for plants grown in containers or plants given special treatments.

Before nursery stock is shipped into the field, it is usually culled to eliminate trees infested with virulent insects or fungi. Culls also include those that have been badly damaged in handling and those with distinctly poor roots. Further segregation should be based more on indicators of the internal physiological qualities that affect survival than on the external appearance of the seedlings (Rose, Campbell, and Landis, 1990; Grossnickle and Folk, 1993). The viability of whole batches of seedlings can be assessed by various destructive sampling techniques to determine their moisture status, carbohydrate content, or ability to form new roots. If seedlings are to be machine planted, it may help to sort them into batches of uniform size.

Culling, grading, and counting the seedlings are best done under shelter as part of the packing operation. These operations should be completed swiftly under cool, moist conditions and handling the seedlings minimally.

Transportation and Storage of Bare-Root Seedlings

If bare-rooted stock is to remain viable, respiration and transpiration must be held to a minimum during transit. Success usually depends on doing both lifting and planting during periods when the trees are dormant or nearly so. It may be possible to move seedlings at other times if the seedlings can be planted in moist soils quickly, as on the same day. The crucial test is the ability of the roots to renew rapid growth after planting. Bare-rooted stock quickly loses this capacity if water and carbohydrates are squandered in transit because the tops are growing too actively or because the plants become too warm or dry.

Planting stock is usually packed in bundles to keep the roots moist and cool while allowing oxygen to enter the package and carbon dioxide and other noxious gases to escape. Traditionally, the bales are constructed of two tight bundles of trees arranged in opposite directions. The tops are open to the air at each end and the roots of each bundle are in close contact with each other. The roots are then covered with sphagnum moss or similar water-holding material, and the whole bales are wrapped with waterproof paper. Provided that they be kept cool, the seedlings can simply be sealed in bags of paper impregnated with polyethylene. These bags allow oxygen and carbon dioxide to permeate through, but are impermeable enough to water that it is unnecessary to include any moss.

The best way to store packages of nursery stock, whether for a few days or over winter, is to refrigerate them at just above freezing. This helps to avoid the desiccation of bare roots that results from freezing. Although they may survive brief periods of freezing if thawed slowly, it is often best not to waste time planting seedlings that were accidentally frozen after lifting. Leafless hardwoods endure storage better than conifers because they are more physiologically dormant. Storage is most commonly done to keep the lifted stock in the early spring dormant for a few more weeks until planting sites in localities colder than the nursery become ready for planting. Seedlings lifted in the fall can also be stored over winter so as to plant on sites that become ready for planting in the spring, before nursery stock can be lifted. This technique is most suited to boreal climates where timing and early spring plantings are essential to get a jump start on a short growing season.

Care of Planting Stock in the Field

If it becomes necessary to store planting stock after it is received from the nursery, it is better to store it in the original bundles in cool places than to store it in the field. As an emergency measure, it can also be "heeled in" on the planting site and taken out as needed. **Heeling in** consists of storing planting stock in a trench dug in moist soil with a smooth, vertical, or slanting side as deep as the roots of the trees are long. The plants are put in this trench in a relatively thin layer and covered with soil up to the root collars. Protection from sun and wind is essential. Ordinarily, several days' supply of planting stock, if kept shaded and moist while on the planting site, will be protected better in the original bundles, than if it were heeled in.

The trees can be carried in pails, baskets, bags, or trays by the planting crews. It is absolutely essential that the roots of the planting stock remain moist until planted. Moss, a puddle of wet mud, or other material for keeping the roots moist is often placed in the container.

Containerized Nurseries

Site Selection

Locating a containerized nursery entails considering many of the same factors of a bare-root nursery: access to water, electricity, and a seasonal supply of labor. However, its location does not need to account for soil or climate aspects. The advantage of containerized over bare-root nurseries is that the soils and other materials for propagation are brought from elsewhere, and the light, temperature, water, and nutrition factors can all be carefully controlled within greenhouses, shade houses, or in some cases, in outside irrigation systems. The ecological location does not matter so much. Containerized nurseries are more centralized in operations and are space efficient, with higher production rates of seedlings than bare-root nurseries (see Fig. 15.3). Because of all the controls in production, seedlings are more expensive to produce. Containerized nurseries have focused on plantings that require more careful control and investment, namely ornamental and urban landscaping, agricultural crops, and trees useful for industrial forestry.

Containerized Seedlings

Under most circumstances, bare-root planting is cheaper, but it has the fundamental disadvantage that it breaks contact between the roots and soil. This constraint can be mitigated by growing the seedlings in containers of soil or soil-like medium, and planting them without ever breaking contact between root and soil (Guldin and Barnett, 1982; US Forest Service, 1989–1990). Containerized planting (also called container-grown planting) is often necessary in arid regions. It is commonly used in the humid tropics, where many species become too large to move several weeks after germination, and must be planted when actively growing and succulent. This problem has traditionally been overcome

Figure 15.5 Mahogany and eucalyptus seedlings growing in polyethylene bags beneath a shade house at a nursery of the Puerto Rico Department of Natural Resources. *Source:* Mark S. Ashton.

by planting both container and seedling. Pots made of quickly disintegrating bamboo or paper are often used, although polyethylene bags (Fig. 15.5) can be used if they are removed or thoroughly slit before the planting.

Saplings more than 3 ft (1 m) tall usually have to be dug out of the ground with large amounts of attached soil. This is then wrapped or "balled" in burlap for moving and replanting. The root systems of such trees are so much more extensive than the tops that many roots are left behind. It is a long time before the saplings are able to resume active growth, and their initial survival may depend on frequent irrigation.

Planting container-grown seedlings or transplants has been systematized and mechanized for a variety of reasons. The most important is that seedlings individually grown in containers in greenhouses grow faster and can be cared for much more effectively than in the open. Among other things, it takes much less seed. This is an important consideration given the high cost of seeds produced in genetic-improvement programs for commercial forestry. Even though containerized seedlings are costly to produce, they can be much cheaper to plant if labor costs are high. Digging holes in the ground is the most costly aspect of hand planting. It takes less labor to punch or bore a hole and install a plant unit of uniform size, sometimes with a special planting tool or machine, than to dig holes for bare-root stock of irregular sizes.

Container Types and their Characteristics

Most containerized seedlings for production forestry are grown (1) as **tubelings** in plantable pots or tubes; (2) as cohesive **plugs** pulled out of containers before planting; and (3) in **blocks** of pressed peat or pulp that are both container and rooting medium (Fig. 15.6). Somewhat similar are "mud-pack" seedlings, which are bare-root stock individually wrapped with soil around tree roots in the nursery shed. Plastic containers are usually best for producing plugs. These are often grown in cylindrical cavities that are closely spaced and inset vertically in reusable molded blocks of Styrofoam. Other more traditional containers, such as polybags, paperbags, or bamboo, are used where access to materials and money is more limiting.

The ideal plantable pot is one that holds together through the planting, and either disintegrates promptly thereafter or does not impede the subsequent growth of roots through the walls. Porous, biodegradable materials such as paper and pressed peat are more suitable than plastic in this respect. When they are planted, the container tops should be covered with soil so that they do not become evaporational wicks that desiccate the soil. The volume of the containers should be uniform. They are often about 2.5 in^3 (40 cm^3).

There is concern about the tendency of elongating roots to be deflected into spiral arrangements when they impinge on the walls of any kind of container. They can even be deformed if they grow against a minute flange on the inside of a plastic casting. Because deformed root systems tend to remain so and produce "pot-bound" seedlings, techniques have been developed to counteract the tendency. One of these is to include vertical grooves or ridges in the container walls so that the roots

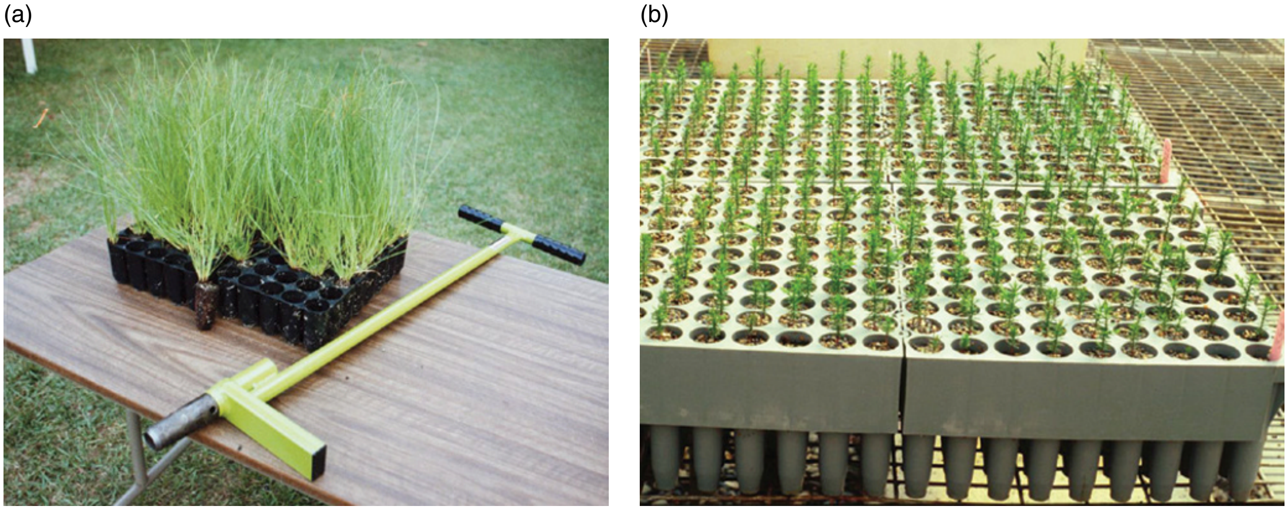


Figure 15.6 (a) Plug seedlings of longleaf pine with the tool that punches holes in which to plant them. When each hole is made, the plug of soil left from the previous hole is pushed out the top of the cutting tube. **(b)** Three-month-old plug seedlings of Douglas-fir. *Source:* **(a, b)** Mark S. Ashton.

are directed downward. Another, called **air-pruning**, involves containers with holes in the bottoms so that there is air beneath them. When the roots reach the air, they stop growing, but they retain the capacity to resume when planted in contact with soil.

Pot-bound seedlings can be avoided by removing them from the containers before the roots touch the walls, but this calls for impossibly good timing. This problem can be reduced by growing seedlings in blocks of peat or pulp such that the roots shy away from the open sides. If the blocks are confined inside containers this obviously will not work. Another way of dealing with this problem is to grow seedlings in plugs and then transplant them into beds within the nursery. These are called **plug + 1** transplants and usually develop dense, cylindrical root systems, and can be produced much faster than ordinary transplants.

Most methods of planting bare-rooted stock also cause deformities in root systems that are merely less obvious than those caused by containers. Unless they have been confined within long-lasting plastic tubes, containerized seedlings probably develop more symmetrical root systems than bare-rooted seedlings that are usually planted with their roots in a single vertical plane like a crack in a rock.

Working Seasons Through the Year

An important advantage of containerized nurseries as compared to bare-root systems is their ability to have year-round production. In comparison with bare-root systems, containerized nurseries can produce seedlings year-round, sometimes two or three crops per year. Carefully selecting the potting medium is perhaps the most critical component of nursery production. The potting medium needs to have good drainage (sand), water-holding capacity (peat), and aeration and buoyancy (perlite). In the right ratio, the mixture can make an ideal medium for germination and growth. Different species will require particular degrees of drainage and texture. Dormancy of seed is broken artificially by using stratification and scarification techniques. Very small seed is usually first germinated in flats under careful humidity control and lighting. Like soils outside, pH is kept slightly acidic to avoid pathogen accumulation, especially damping-off fungi (*Fusarium* spp., *Phytophora* spp.). Most commercial forestry and horticulture standard production systems use plugs, blocks, and tubes for containers. Young germinants grow rapidly under controlled shade, humidity, and temperature. Automated irrigation booms supply water and nutrients. Because of the confined conditions, insects and disease can spread rapidly, so vigilance and immediate control are important. Most reforestation stock produced in tubes or blocks for commercial forestry is out in a plantation within 6 months. It germinates in early winter for a spring planting, or in spring for a fall planting. However, many ornamentals and urban stock need to be large and require a series of transplantings to larger pots moved to semi-environmentally regulated greenhouses, and then eventually to the outside as an iterative process of hardening off. Urban trees are eventually ball-and-burlapped or placed in pots buried in beds outside (see previous section on containerized seedlings).

Transportation and Storage of Containerized Seedlings

If necessary, dormant containerized seedlings can be stored under whatever conditions of low temperature or dryness that they have evolved to endure in nature. Since the roots are not exposed, there is no need to freeze

them if they are dormant and the species are adapted to frozen soils. If they are about to be planted, however, they should be actively growing or capable of surviving at the time of planting. Containerized stock is shipped to the field when the time is suitable for planting. The timing and mechanization of lifting is not problematic, compared to the way it is with bare-rooted seedlings. Sorting and culling are usually finished during the growing process. If the containers are shipped out with the seedlings, packing consists only of putting the material in crates or on racks designed to prevent crushing the seedlings. If the containers are for growing plug seedlings and are to be reused, there is the cost of returning the containers back to the nursery.

If plug seedlings are withdrawn from the containers before shipping, they need to be dormant. Generally, they are packed in polyethylene bags or in coated boxes for better protection of plugs. They can be put in cold storage if desirable. Plugs lose their cylindrical shape during all this handling, so they cannot be planted in standardized holes. The chief advantage is that the containers do not have to make a round trip to the planting site. Whether or not the containers survive the trip, the main shortcoming of containerized planting is the simple but arduous and costly task of moving so much material to the dispersed spots where trees are planted.

Vegetative Propagation of Planting Stock

Planted trees do not always have to be grown from seed. It can be advantageous to bypass sexual reproduction and germination problems. In the first place, asexual regeneration by vegetative propagation is the only sure way of perpetuating trees with the same parental genetic qualities. Second, if **cuttings** of a species form roots readily, it may be much easier and provide quicker results to plant them rather than to grow seedlings. Even if it is difficult to make cuttings of old plants to form new ones, it can still be advantageous to do it in order to rapidly increase the number of individuals with highly desirable genetic characteristics.

With some species, such as the cottonwood poplars, it is possible to merely plant long pieces of thin shoots and expect most of them to form roots and become established (McKnight, 1970), but this usually happens only on moist soils. Sometimes, as with sycamore, dense stands can be created by burying branches in shallow trenches and having each branch produce many shoots.

Most tree species cannot be propagated from cuttings this easily. In fact, it is so difficult for most species that propagation is used mainly to multiply valuable ornamentals, fruit trees, and trees for seed orchards. Such work is usually done in greenhouses with the use of rooting hormones such as indolebutyric acid (IBA).

More sophisticated techniques are used to produce whole new plants from culturing small fragments of tissue in media that supply the complex biochemical substances needed for plant development (**tissue culture**) (Bonga and Brown, 1982). Plantlets produced by such intensive methods are normally transplanted to containers for further growth before planting. Though the tissue culture method has now been around since the 1970s, it is still not used widely in forestry and is specialized for particular horticultural and agricultural crops.

There are potential advantages of creating forests from asexually regenerated genetic material. Forest tree species have not been subjected to millennia of genetic selection by people and are therefore still very heterozygous. This genetic heterogeneity can make it difficult to replicate individuals with many fine genetic traits with controlled-pollination schemes. With vegetative propagation, it is not possible to improve upon nature, but the best individuals can be multiplied. In horticulture, varieties of cultivars have probably used vegetative propagation to the extreme. This has made such enterprises susceptible to disease, insects, and climate. However, in forestry, the very nature of the development of stands of woody plants and the vicissitudes that long-lived perennials must endure, are such that it would be undesirable to create highly uniform stands of single genotypes. Genetic resources must be managed both to multiply socially desirable genotypes and to preserve diversity.

Working Seasons Through the Year with Vegetative Propagation

Most nurseries that focus on vegetative propagation are containerized operations, because the techniques require close control of humidity, temperature, water, and light, to facilitate rooting and bud formation. Cuttings can be leaves, stems, or roots depending upon the species. For trees and shrubs, almost all cuttings are taken from the stem, but many herbs can vegetatively reproduce from leaves, and grasses and bamboo can reproduce from roots.

The hormones used to facilitate germination can also be applied in mixture as powders or dips to the cut stems, roots, or leaves of cuttings, before inserting the cutting into the potting medium. Auxins (IAA, IBA) promote callus and cell division, cytokinins promote bud initiation from calluses, abscisic acid (ABA) promotes root initiation, and giberellins promote stem elongation. In addition to the use of hormones, it is important to: (1) take the cutting from the part of the plant that is most likely to callus; and (2) take the cutting at the most appropriate time and season. In regard to the location of the plant to take a cutting, the lower lying lateral branches that have young juvenile growth are best. In regard to the timing, cuttings should be taken just before breaking dormancy in the early spring (in tropical or arid climates just before the rains). The rationale is to ensure the cutting has high amounts of stored carbohydrate that can be reallocated to the development of new roots and shoots.

Figure 15.7 Cuttings of western redcedar in propagation blocks. *Source:* Mark S. Ashton.

Cuttings can be propagated in several different ways depending upon species. Some can simply be placed in moist sand in the spring and they will take root (Fig. 15.7). Others can be propagated in the same manner in the fall. Still others can be placed in plastic bags within coolers that both increase humidity and reduce heat and transpiration stress. These three modes of propagation can be incorporated into bare-root operations. However, many species need to be placed in large trays of sand that are maintained with a humid mist and warmed from below with heat (**bottom heat callusing**) to induce callus and root initiation.

Once the cuttings have "taken", they can be lifted out of the trays or beds that they initially were rooted in, and transplanted into pots. After the cuttings are in pots, they follow much the same routine as containerized seedlings.

Grafting

The purpose of grafting is to unite a hardy seedling root, called the stock, with a cut stem, called the scion. The scion is the aboveground part of the plant that produces the future value of the tree that is being sought (e.g., fruits, nuts, flowers, aesthetic forms). An example of a widely used graft is that between the root stock of native North American grape (the fox grape) to the scions of varieties of grape used to produce wine. Other well-known examples are combining the root stocks of apple, plum, and pear species with the scions of a great number of fruit cultivars, the graft of the native North American black walnut to the English walnut scion, and the large numbers of varieties of weeping ornamental trees to their matching native erect species root stocks. Grafts are very common in ornamental, urban, and agroforestry use. Trees used for reforestation, restoration, and plantation forestry do not use grafts. There is no rationale for their use. Grafted trees are susceptible to breakage at the union in winds, and need careful tending. Such trees would not do well on their own. Two major kinds of grafts are used for seedling propagation: 1) **tongue or whip grafts**, and 2) **side grafts** (see Box 15.1).

Box 15.1 A description of the mechanics of grafting with illustrations for tongue and side grafts.

The practice of grafting has developed over thousands of years, and while technology and technique have changed over the years, the principles remain the same. In essence, grafting is the combining of two plants' vascular systems. In practice, this usually involves attaching a cut shoot from a donor plant to some type of understock on a receiving plant. The cut shoot that will grow into the top part of the plant is called the **scion**, and the receiving root system is called the **stock** or understock. The term rootstock is used when only the root system is kept from the receiver plant. The terms stock and understock are used when some part of the stem of the receiving plant is kept. The resulting plant is not a hybrid because each part of the plant retains its genetic identity. However, plant organs exert influences on other parts of the plant and a grafting plant will thus exhibit characteristics of both stock and scion. For instance, dwarfing rootstock will create a dwarf variety of the scion, while the scion will produce its characteristic fruit and flowers.

The simplest grafting situations involve one scion and one stock. However, one can add interstock in the case of double working to create linear fusion of three plants, where characteristics from all three are desired. Bud grafting, or

(*Continued*)

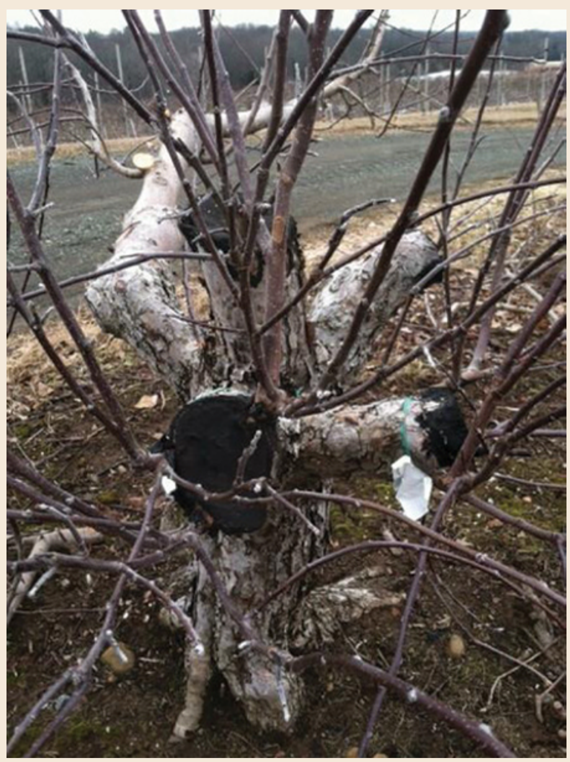
budding, refers to the grafting of a single bud onto stock. Grafting techniques are most often used for fruit, nut, ornamental trees and shrubs, cloned forestry trees, and in more limited applications, vegetables. Vegetable scions are often grafted onto rootstocks that confer resistance to common diseases and pests.

There is a variety of methods for attaching scions onto stock. All methods aim to create vascular continuity between the stock and scion. Cell division rapidly occurs on the cut surfaces to create callus tissue. Once the calluses reach each other, they differentiate into cambium cells and establish vascular continuity. While a number of grafting methods exist, most fall into three categories. A commonly used technique for grafting stock and scion of the same size is "whip and tongue" grafting (Fig. 1). When joining a scion to a larger-sized stock, "side grafting" is often used (Fig. 2). In the case of top working, which is often used in orchards to switch from one tree variety to another, "cleft grafting" is commonly used (Fig. 3). In many situations, stock leaves or branches are left intact to feed the rootstock until the scion is fully grafted and can begin to feed the rootstock itself.

With any technique, avoiding desiccation of the scion is critically important during grafting. Because the scion is no longer connected to roots, water lost to transpiration is not replaced. Scions should be well hydrated before grafting. Managing air moisture by grafting in greenhouses or putting plastic bags over scions can also help reduce desiccation. Grafting should also take place under conditions that are warm enough to encourage plant physiological processes (i.e., cell division) but not so warm as to cause high transpiration. This optimal temperature can vary among species. In temperate climates, early spring or early fall are the best times for grafting.

Box 15.1 Figure 2 Side grafts on western hemlock. *Source:* Mark S. Ashton.

Box 15.1 Figure 1 Whip graft on Douglas-fir. *Source:* Mark S. Ashton.



Box 15.1 Figure 3 Top working using cleft grafts on apple. *Source*: Mark S. Ashton.

Planting and Seeding

Planting Considerations

Planting Season

Success in bare-root planting depends on doing it when periods of 2–3 weeks of active root growth can be anticipated before bud break, such as early spring. The use of containerized stock gives more latitude in timing than is available with cuttings or bare-rooted seedlings that are directly out-planted. Roots normally grow at times of the year when supplies of reserve carbohydrate and water are available. However, this can be overridden by the demands of rapid shoot or leaf formation (Jenkinson, 1980).

In climates that induce dormancy and stop growth in seedlings because of periods of cold or dryness, plants break dormancy and experience rapid root growth just after the warmth of spring (cold temperate climate) or at the onset of rains (dry tropical or Mediterranean climate). The best time for planting comes just before that, because of the opportunity for quick reestablishment of contact between plant and soil, and because the whole season is available for further growth.

Bare-root planting must be done in a short period at the beginning of the growing season. If the period is brief, the operations that start with lifting and end with planting are apt to be frantic, costly, and sloppy. If the lifting must be delayed by waiting for the nursery beds to thaw or stop being muddy, the season has to be shortened even if the planting sites are ready. Lifting in the fall and storing the seedling is one way to start the planting earlier for the next growing season. If soil moisture and temperature are adequate, there may be another period of active root growth in the autumn, when trees that have hardened and formed buds can then be planted with fair success. However, not all species in the same locality have the same seasonal regime of root growth. Thus, it is best to plant at the time and season when roots can be depended upon to grow actively after planting. A major advantage of containerized planting is that it can be done at times when bare-root planting cannot. Container-grown seedlings can extend the planting season and the survival for containerized stock is significantly higher compared to that for bare-root stock.

Bare-root planting should not be attempted when the air temperature is below 32 °F (0 °C) or when hot or dry winds are blowing. If trees are planted in the autumn in cold climates, frost heaving can cause serious damage during the winter, especially if the trees are not well covered by an insulating blanket of snow. Another drawback to autumn planting is that the seedlings do not get the benefit of a full growing season of carbohydrate production. Trees are generally storing carbohydrates at those times of year when water is available but formation of new tissues has ceased. They may continue to gain weight late in the autumn, even if their dimensions do not change. In some warm climates, such as the southeastern US, spring and autumn are, in effect, merged, so that planting is done during the mild winters. It may, however, have to be suspended during temporary periods of freezing weather.

Site Preparation

Successful planting often depends on measures such as reduction of competing vegetation, removal of physical obstacles to planting, and drainage of water toward (too dry) or away (too wet) from the planted trees. Most of these measures are dealt with in Chapter 7 (Site Treatments).

Control of competing vegetation is especially important because many planting sites are already crowded with preexisting vegetation. Unless a vacancy is found or created in the growing space, it will be difficult for a planted seedling or transplant to survive or grow satisfactorily. Site preparation as a means of controlling competing vegetation is usually done as a separate operation. However, planting spots can also be prepared at the same time as the planting by spot applications of herbicides or scalping. **Scalping** is the scraping of competing vegetation from the planting spot with hand tools. It is moderately effective against thin grass or very low shrubs, and can be done with the grubhoes that are sometimes used in planting.

Pre-planting site preparation by itself is not always enough to eliminate all problems with competing vegetation. In fact, it may aggravate problems by enabling overwhelming invasions of weeds. There will be competing vegetation simply because the planted trees will not immediately fill all the available growing space. Sometimes, it helps to limit site preparation to small planting spots and use the other residual plants to exclude more aggressive pioneer competitors.

Methods of Planting Bare-Root Seedling Stock

An increasing number of hand tools and machines can be used to make planting holes, insert seedlings, and pack soil back around roots (American Society of Agricultural Engineering, 1981).

Successful planting depends on the ability of the roots of the planted seedlings to regain contact with the soil to resume the uptake of water and nutrients. The first essential rule is that the roots be placed in soil with immediately available water. The moisture content must be well above the wilting point, and the soil temperature must be sufficiently above the freezing point that water can move readily. Moist mineral soil is by far the most dependable water source. Organic materials are not reliable unless they are peats and mucks situated so that they remain close to saturation without being oxygen deficient. The soil must also be warm enough for roots to grow.

When bare-rooted nursery stock is lifted, virtually all of the mycorrhizal mycelia and root hairs that constitute the main absorptive portion of the roots are destroyed. Until these unicellular strands resume proliferation, the plant has no means of absorbing water that is not immediately adjacent to the existing roots. Fortunately, brown suberized roots can absorb water directly (Kozlowski, Kramer, and Pallardy, 1991), thus providing planted trees with an immediate but limited supply of water. This is one of the reasons why it is so essential that the soil be solidly packed around the roots of plantings.

Until the main absorbing network redevelops, the planted seedling has only slightly more ability to capture moisture than a cut flower in water. The development of new root hairs depends on the elongation of new adventitious roots and root tips, many of which are broken off during lifting. New root tips must form before any major portion of the permanent and readily visible part of the root system can extend itself in the soil. The root system of a planted tree elongates rapidly only during limited periods when the normal physiological rhythm of growth is directed toward this process. Furthermore, it is reasonable to suppose that such root elongation will not happen rapidly until photosynthesis becomes vigorous again. Because this is not likely to occur until the active absorption of water and nutrients resumes, any complete dependence on elongation of root tips and on absorption by root hairs would jeopardize the survival of planted seedlings.

Mycorrhizal mycelia are probably much more effective than root hairs in reestablishing early contact with the soil. The fungi that are involved need only a supply of reserve foods from the plant and the proper conditions of moisture and temperature to resume growth. Consequently, they do not depend on resumption of complete activity by the plant to be effective in absorbing water. It is significant that most tree species normally enter into mycorrhizal relationships and may require them to survive or thrive after planting. Unfortunately, soil sterilants, that are often applied before seeds are sown in nurseries to kill weed seeds and control other pests, also kill mycorrhizal fungi. This problem is overcome by artificial inoculation of the soil with appropriate fungi (Marx, Cordell, and Kormanik, 1989; Oliviera *et al.*, 2010). The strains introduced are sometimes better than the natural ones, and sometimes the appropriate inoculum is nothing more than litter from beneath trees of the host species growing in their natural habitat. When exotic tree species are introduced to a locality, it may be necessary to bring the appropriate fungus species as well. However, it is prudent to test native fungi first, and it is mandatory to adhere to regulations about the introduction of species that can become pests.

Seedlings should usually be planted at the same depths that they occupied in the nursery. Sometimes it is advantageous to plant them deeper, but never more shallowly. If the depth of the plants gets lower, there is a better chance of the roots accessing the water. One useful indicator is the root collar, which should always be right at the surface of the mineral soil after planting.

In reforestation plantings, roots that are longer than 8–10 in (20–25 cm) may be too long to plant properly. It may be desirable to prune the ends off before giving the seedlings to the planting crews. Every precaution must be taken to ensure that the roots remain visibly moist at every stage of handling. Seedling roots should remain covered until the moment they are planted and not waved around in the air. Moist soil must be packed around the roots, and the planting holes should be filled completely, leaving no air spaces. Litter or other organic debris should not be used for filling the holes unless the soil itself is organic. The seedlings should be planted firmly enough to resist a gentle tug with thumb and forefinger.

Any mode of root placement resulting from planting is unnatural (Van Eerden and Kinghorn, 1978). Seedlings are ordinarily planted with stems erect and roots spread out in a vertical plane. This pattern is not desirable with species such as the spruces, which have roots that characteristically grow in a horizontal plane. There are special techniques for planting trees with the roots so arranged.

The greatest problems arise from sloppy planting that leaves the roots curved upward like the letters J, L, or U. The roots should be placed more deeply into the planting hole. If not, then the roots do not develop the symmetrical structural pattern necessary for windfirmness and become vulnerable to uprooting after they grow tall. This problem is greatest in root systems that are wound into balls when stuffed into shallow holes, or left to grow too long in containers. If roots are too long, it is definitely better to prune them than to force them into contorted shapes when planting them. Natural growth of new roots does correct some of the abnormalities of root systems of planted seedlings, but seldom perfectly. The stems of most species will straighten up if the stems are not perfectly erect, but some, such as the larches, will not.

Regardless of whether the work is done by hand or with machines, the same general methods are used to make holes and plant bare-rooted seedlings. In the **compression methods** (**bar-slit** and **grubhoe-slit**), holes are made for the plants by pushing the soil aside with sharp instruments into the ground. After the tree is inserted, the soil is pressed back around its roots. In the **dug-hole methods** (**center hole**, **side hole**, **wedge**), the soil is actually removed and set aside to be repacked around the roots after they are arranged in the hole. All methods of hand planting also involve the use of the heel to repack the soil around the tree roots (see Box 15.2 for details on planting methods).

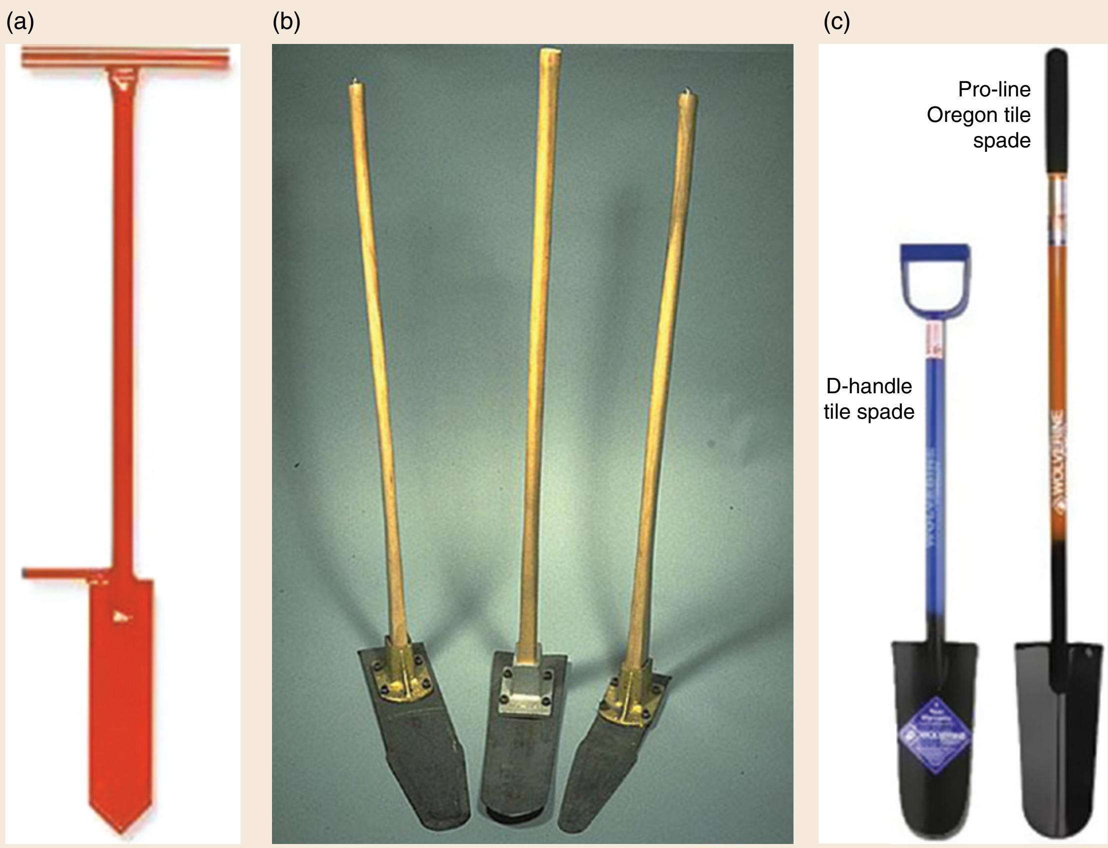
Box 15.2 Methods of planting bare-root seedlings.

Several types of heavy dibbles or planting bars, such as the one shown in Fig. 1, can be used for planting trees in sandy soils. The most common technique for using such tools, known as the **bar-slit method**, and shown in Fig. 2, illustrates the basic principle of the compression methods. In this method of planting, it is important to push the seedling down deeply into the hole and then partly withdraw it so that the roots will go as deeply as possible but be straightened out and free of J-bend or U-bend. One continues to hold the seedling upright while pushing the soil back against its roots. Because one person does all the work in this method, it helps to carry the seedlings in a shoulder bag (Fig. 3) rather than in a container that is set on the ground; by using a planting bag, one bends over only once for each tree. One can plant an average of 1500 trees daily with this fastest method of hand planting.

On soils that are stony or have so much clay that they become compact under true compression, a modified compression method can be employed. Grubhoes are used in this **grubhoe-slit method**. The soil is partially lifted from the hole rather than pushed aside. A person can plant about 700 trees daily with this method. One advantage of the grubhoe is that it can be used for scalping, whereas planting bars cannot.

The main drawback of the compression method is the difficulty of being certain that the holes are completely closed or that the roots of the seedlings are free of U-shaped bends. These problems can be partially avoided by refraining from working the blades of the tools back and forth after driving them into the soil. The holes created as a result of this error are shaped like hourglasses in vertical cross-section; it is difficult to work the roots past the constriction and impossible to be certain that the lowest part of the hole is closed. Even the grubhoe modification of the compression method may be difficult to apply in soils that are very stony or cohesive.

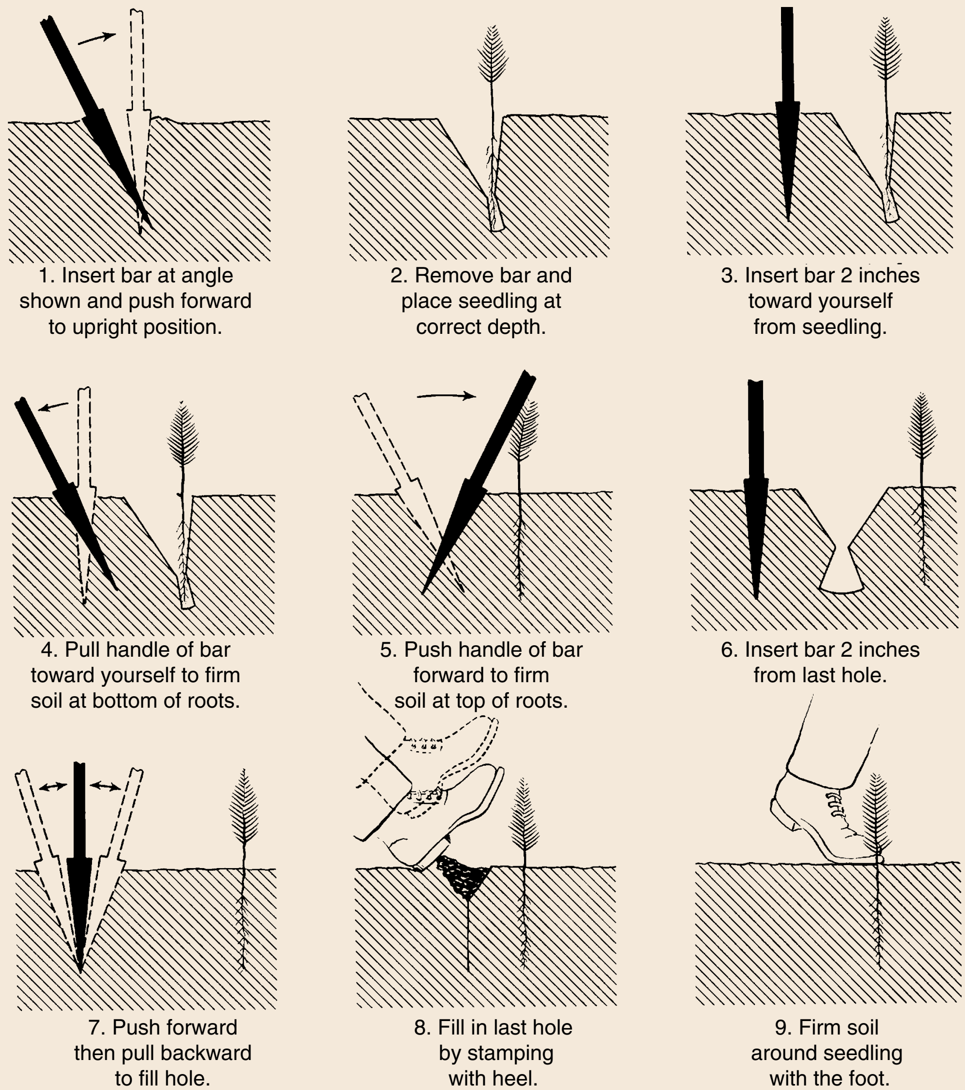
The **dug-hole methods** must be used where the compression methods fail to give good results. Grubhoes (Fig. 1) are usually employed in this method, sometimes with one person digging the holes and another doing the planting. The holes are made sufficiently wide and deep to accommodate the roots of the trees. The mineral soil is



Box 15.2 Figure 1 Three tree-planting tools. **(a)** A pointed planting bar useful in stony soils. **(b)** The Rindt grubhoe (L-shaped) for making straight-sided planting holes. **(c)** A tile spade planting shovel for digging deep holes for larger planting stock. *Source:* **(a–c)** B. Meadows, Ariens Specialty Brands LLC. Reproduced with permission from B. Meadows.

(*Continued*)

Box 15.2 (Continued)



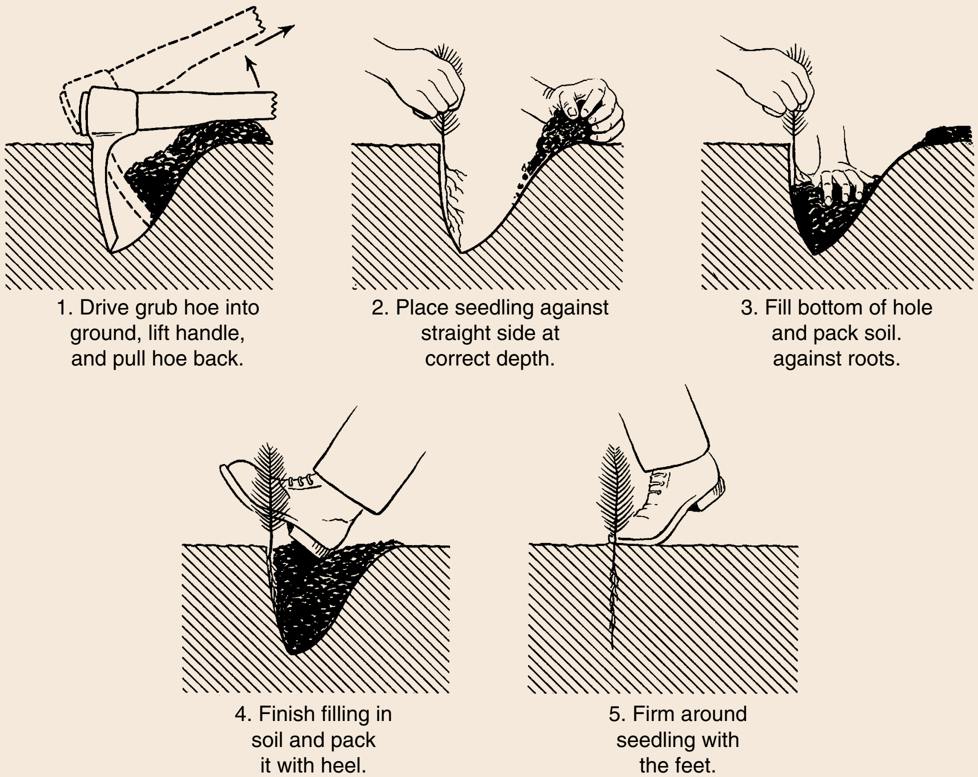
Box 15.2 Figure 2 Steps in the use of the bar-slit method of planting seedlings in sandy soil. *Source:* US Forest Service.

(a)

(b)

Box 15.2 Figure 3 **(a)** A professional tree planter with a tile spade and planting bag working to reforest after a wildfire. *Source:* L. Forsyth. Reproduced with permission from L. Forsyth. **(b)** A planting bag. *Source:* Forestry Suppliers, Inc. Reproduced with permission from Forestry Suppliers, Inc.

Box 15.2 (Continued)



Box 15.2 Figure 4 The side-hole method of planting. *Source:* US Forest Service.

piled beside the hole separate from leaves, sod, and other debris to facilitate planting and to ensure the use of clean soil next to the roots. The trees are planted entirely by hand immediately after the holes are dug so that the exposed soil will not become desiccated. Several different methods can be used to shape the holes and plant the trees.

The simplest dug-hole method is called the **side-hole method** (Fig. 4). One side of the hole is left smooth and vertical; the roots are spread out against this wall and packed firmly in place by hand with a thin layer of fresh, loose soil. The rest of the mineral soil is then scraped into the hole and trodden down with the heel. Usually, the area around the hole is scalped before the hole is dug so that the tree will not be immediately adjacent to competing vegetation. This method can be used under almost any conditions but is not rapid; the production rate is about 600 seedlings per person-day. It leaves the roots in a vertical or slightly curved plane.

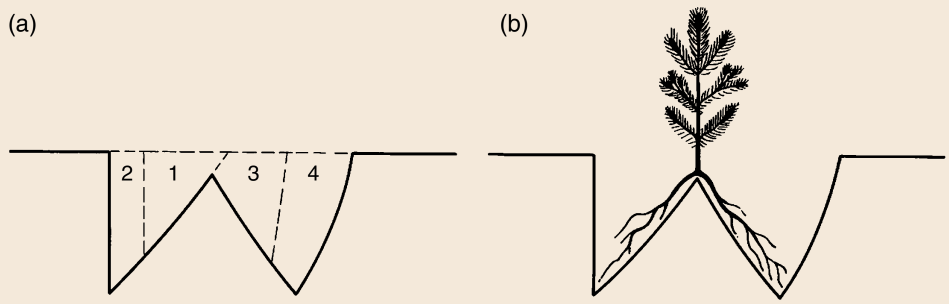
The best way to get the roots placed in three dimensions is the **center-hole method**. This involves putting the tree in the middle of the hole and then sifting and packing the loose soil between the various strands of roots, without forcing them into either a horizontal or vertical plane. This is a slow method, but it can be speeded by boring the holes (with motorized augers).

The **wedge method** is another way of improving root placement. It involves creating a hole with a ridge in the middle such that a vertical cross section would resemble the letter W (Fig. 5). Half of the roots of the tree are spread out on each sloping surface and tamped down in that position. Rudolf (1950) described how the holes could be made with several strokes of a grubhoe, and stated that 500 trees per person-day could be planted by this method. This procedure is well adapted to the planting of species such as the spruces, which have distinctly horizontal root systems.

Perfectly horizontal placement of roots can be achieved by techniques such as making T-shaped incisions in turf with spades, turning up the resulting flaps, spreading out the seedling roots, and then tamping the flaps back over them.

(*Continued*)

Box 15.2 (Continued)



Box 15.2 Figure 5 The wedge method of planting as described by Rudolf (1950). **(a)** The sequence in which soil is removed by four strokes of a grubhoe to create the hole. **(b)** The tree ready to be tamped in place. *Source:* US Forest Service.

Methods of Planting Containerized Seedling Stock

Containerized seedlings (Barnett and McGilvary, 1981) can be planted with special devices of varying sophistication, provided that the units to be planted have retained sufficiently uniform size and shape. One of the advantages of using uniform units is the opportunity to poke standardized holes in the ground, rather than doing laborious digging. This advantage is of greatest importance with stony soils where digging is difficult. The simplest devices, suitable only for small stock, are nothing more than rods stuck in the ground. These can also be used for planting cuttings of such easily rooting species as the cottonwood poplars. There are also devices that make holes by compression and either set or shoot the containerized material into the soil.

If the container units are not a uniform size and shape, they are put in the ground by the same hand or machine methods used for bare-rooted seedlings. This is common with plugs that are extracted from the containers before being shipped to the field.

Most street trees and planting in urban environments grow seedlings into saplings over a period of years, sequentially transplanting the seedling stock into larger and larger containers. This is done primarily because smaller stock has very poor ability to survive the stresses of the urban environment. Eventually they are moved to burlap (Fig. 15.8). The actual planting process is time consuming and expensive. In general, the width of the hole should be about three times larger than the container or root ball. If large bare-root stock is used, which is becoming more popular because of the logistical ease of moving the sapling without the container and soil, the width of the hole should be at least three times the length of the roots. The hole should be no deeper than the depth of the ball-and-burlap or container, such that the root collar/root flare is just above the soil surface when planted. The soil removed from the hole should be mixed with topsoil loam and organic manure to supplement the poor-quality soil usually found in urban environments. The soil surface should have a protective mulch added that should be raised as a ring around the center of the planted tree to direct water into the roots. Newly planted trees should be watered at least once a week for the first growing season to ensure survival.

Planting Machines

Sites that are level or gently sloping and free of stumps, rocks, slash, and tree roots are the best places to plant with machines. Except where labor is cheap, or where the terrain is unsuitable, it is better and cheaper to plant trees with machines than by hand. Abandoned agricultural fields are the ideal places for the machines. It is unwise to remove stumps and logging debris simply to enable use of planting machines. Damage to the soil may be too great, and the resulting total costs may exceed those of hand planting. For these reasons, most replanting after logging is done by hand.

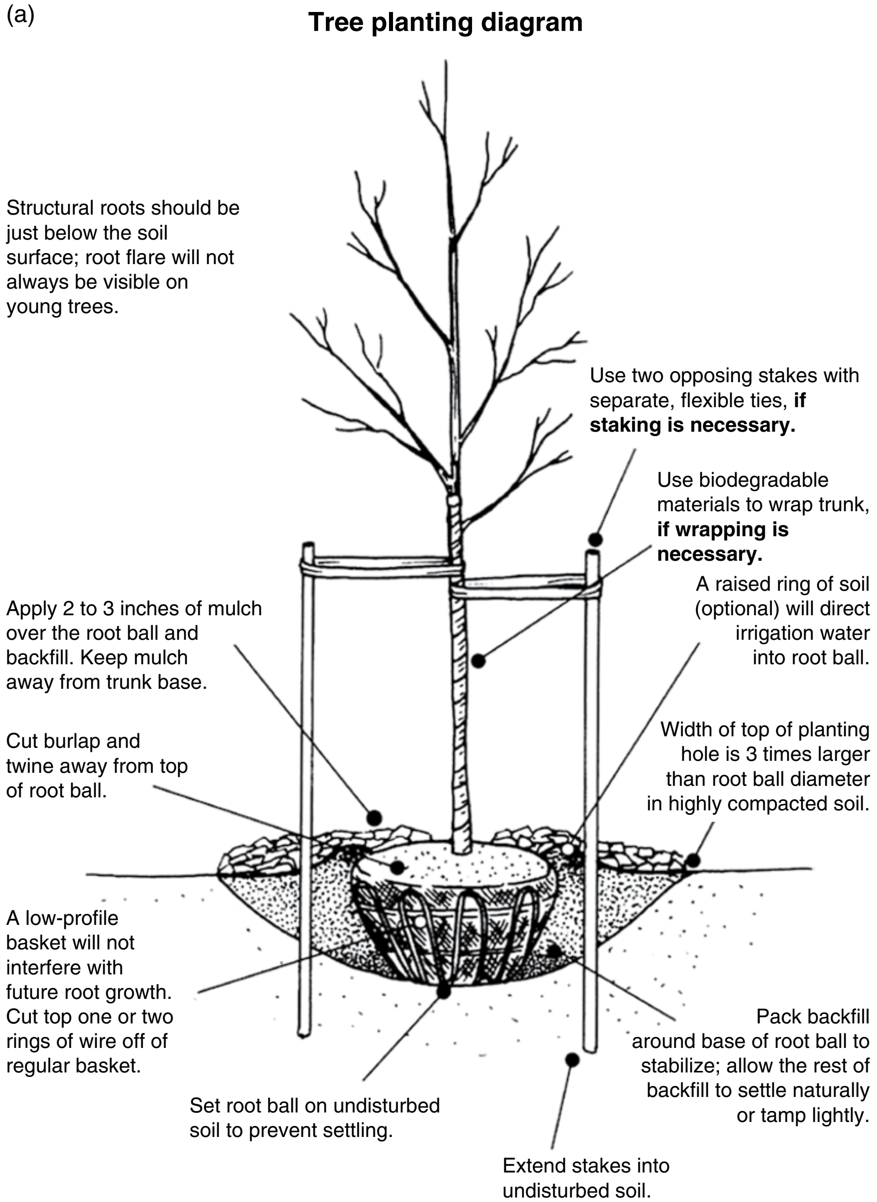
Most planting machines operate with the compression method. The typical machine (Fig. 15.9) cuts a narrow trench through the soil with a specially designed plowshare. The seedlings are placed in a slot just behind this trencher, and the soil is pressed firmly back around the roots by two wheels that are mounted close together in slightly tilted positions at the rear of the machine. The machines are heavy enough that seedlings are usually planted more firmly than is possible with use of the human heel. They can plant from 4000 to 15,000 seedlings per day, depending mainly on site conditions.

Placement of Seedlings and Reshaping of Soil Surface

Most techniques used to treat vegetation and soil in preparation for planting were discussed in Chapter 7. Bedding is covered here as an actual part of planting. Some techniques involve making furrows or ridges. If the soil is too wet, planting is on the tops of the little ridges.

Figure 15.8 (a) A diagram illustrating the process and considerations of planting a street tree. *Source:* Adapted from Chicago Center for Green Technology. **(b)** An example of a ball-and-burlap tree that is about to be planted by The Urban Resources Initiative of the School of Forestry and Environmental Studies in New Haven, CT. *Source:* P. Otis. Reproduced with permission from P. Otis. www.peterotisphotos.com.

(a)



(b)

(a)

(b)

Figure 15.9 (a) An old photograph showing the essential parts of a tree-planting machine that have not changed in half a century of use. The round cutting disk or coulter (at right) cuts through roots and sod ahead of the split plowshare or trencher. The trees are put down in the slit made by the trencher between the two wings or guides at its back end. They are then tamped in place by two-tilted rubber-tired wheels mounted at the rear of the machine. *Source:* Louisiana Forestry Commission. **(b)** Six-month-old seedlings of loblolly pine planted by a trencher machine on a site that has been drum-chopped and herbicided. *Source:* Yale School of Forestry and Environmental Studies.

If it is too dry, seedlings are planted in or near the bottoms of the furrows. However, if furrows are made to use folded-over sod or other turf to uproot and also cover competing vegetation, it becomes logical to plant trees along the lines where the ridges and troughs intersect. In this way, the trees are kept as far as possible from competition, and also have their roots partly in the soil strata in which nutrients tend to be concentrated.

If the soil is too cold, it can be made warmer by removing litter and creating small ridges on which to plant the trees. Sometimes slotted circles of mulch-like paper with holes in the centers are slipped around planted trees to shade out competing vegetation. Localized applications of herbicides can be used to produce the same effect, but care must be taken not to kill the planted seedlings.

In very dry situations, it is essential that seedlings are planted in basins or on terraces designed to concentrate runoff of water (Goor and Barney, 1965). Stones can be placed around the seedling stems to shade them, to

redistribute water, and to restrict direct evaporation from the soil. It is important to note that it is possible to store significant quantities of water if infiltration can be concentrated in localized spots. A disproportionate amount of water then sinks into the deeper soil that is wetted to **field capacity** (the amount of water that can be held against gravity). If it is uniformly distributed over the surface, much of it is likely to be lost to direct evaporation or transpiration by shallow-rooted vegetation. However, if it can be concentrated around planted trees, deeper columns of water can be stored in such a way that seedlings may still have some available even once the soil close by is depleted. The same general effect can be achieved where snow accumulates in drifts. The main point is that trees can be established in semi-arid conditions if water can be concentrated in the planting spots.

Direct Seeding

The direct sowing of seeds to establish forest stands is a technique of artificial regeneration that should work, but does so only under special circumstances. Success in natural regeneration usually depends on whether a very small proportion of a very large quantity of seed lands in favorable spots and is overlooked by all the animals that feed on seeds. This random process could ordinarily be duplicated artificially only by broadcast distribution of hundreds of thousands of seeds/acre (hectare). That would be much more costly and not often as successful as planting. In establishing stands by direct seeding, the odds against success must be reduced by: (1) careful protection from or avoiding seed-eating animals, and (2) distinctly favorable conditions of site and seedbed. Success also usually depends on whether there is sufficient rain after sowing to keep the uppermost layer of soil adequately moist throughout the period of germination and the succulent stage.

Seed Supply

Direct seeding requires large amounts of seed that should be gathered and handled in the same ways as to supply tree nurseries (see prior section on seed collection). If possible, seeds should be harvested from special seed-production areas or seed orchards. The precautions about choices of species, geographical origins, and genetic characteristics discussed in Chapter 14 are also relevant.

Most problems arise from the difficulties in gathering cones or fruits from tall standing trees. The work is hard, and the period during which it can be done is usually short. Crops worth harvesting are likely to be produced only during sporadic good seed years.

The best seed producers are ordinarily dominant, healthy trees that have reached middle age. The likelihood that their seeds will be of acceptable genetic quality is greatest if similarly mature trees are close by to provide pollen. If good, younger, and shorter trees produce adequate amounts of fertile seed, it is acceptable to collect their seed. Unfortunately, it is simpler to gather seed from short, easily climbed, deep-crowned trees of poor form, than from tall, straight, well-pruned ones. Although poor form in the parent does not necessarily indicate that its progeny will also have poor form, experience suggests that it can increase the possibility.

Protection from Seed-Eating Animals

Almost any site that supports a forest, or is capable of doing so, also supports a large population of small mammals, and is combed over periodically by birds seeking food. These seed predators are rarely obvious to casual inspection, especially during the middle of the day. These populations vary widely in time and space. Variations in foraging between seasons and between years can be large. In general, areas of barren soil will support lower populations of small mammals than those covered with vegetation or litter. These also offer less shelter to seed-eating birds. In direct seeding, it is good to take advantage of places with low animal populations.

Site preparation to reduce the amount of soil cover is very important in improving germination and survival of seedlings, but is not especially effective in controlling the seed predators. Screens and live traps can be effective, but are so expensive that they are useful only for research purposes. Rodents have a good sense of smell and are rarely outwitted by covering the seeds. The wholesale poisoning of rodents on regeneration areas is both unethical and illegal in many areas. Also, if the population of seed predators is reduced, this merely creates an ecological vacuum. Breeding or reinvasion can restore the population even during the period that seeds remain edible.

During the 1950s, direct seeding became practical because of the development of chemicals that effectively repelled small rodents and birds (Abbott, 1965; Derr and Mann, 1971). An ideal repellent is a compound that makes the seeds distasteful to the predators but does not kill them. The early rodent-repellent compounds were effective at the low dosages in which they were applied, but were prohibited in the 1980s because they were either dangerously toxic at higher dosages or excessively persistent. More recent studies have shown that seeds treated with capsicum and thiram are effective against mice and can be used on seeding areas (Nolte and Barnett, 2000), and anthroquinone has proven to be effective against birds (Avery *et al.*, 1998). Some species, such as birches, spruces, eucalypts, and western redcedar, have seeds small enough that they are not especially subject to predation. Sometimes these can be sown without repellents. However, the lack of generally acceptable repellents has greatly curtailed use of direct seeding.

Effect of Site Factors and their Modification

Success in direct seeding also depends on rendering the microsite as favorable as possible and ensuring prompt germination. The seeds should be placed in contact with mineral soil, and, if possible, covered to the greatest depth consistent with successful germination. Moisture must be almost continuously available at or close to the surface of the mineral soil until the seedling roots have penetrated to a stable moisture supply below. The amount of water several inches (centimeters) below the surface that might support a newly planted tree is not necessarily sufficient for a newly germinating seedling. Consequently, some climates are too dry for successful direct seeding.

The most favorable soils are those that are well supplied with moisture because of their topographic position, though poor aeration in excessively wet spots can also cause failure. Moist, but well-drained soils that are supplied with water by seepage from higher ground are also very favorable. Soils of extremely coarse or extremely fine texture are less favorable than those of loamy texture.

As far as the germination and initial establishment of seedlings is concerned, a light cover of vegetation over bare mineral soil is ideal. It allows the seeds to come in contact with the mineral soil while it shields the surface from direct sunlight, thus reducing heat injury and direct evaporation from the soil. Desiccation of most of the soil layers is mostly because of water removal by transpiring plants, but desiccation of the surface and about the first 0.5 in (1 cm) of soil is caused more by direct evaporation. Therefore, the vegetation that restricts the supply of water to a well-rooted seedling can actually increase the amount of water available during germination and the crucial days thereafter. Such annuals as mustard and rye have been useful when sown in mixture with conifer seeds on bare mineral soil. They do not reappear during the second year and may serve to exclude undesirable plants as well as provide shelter during the first year.

The shade of woody plants is beneficial in the early stages, but its ultimate effect depends on the extent to which it competes with established seedlings for light, water, and nutrients. The best shade is that which is cast by dead materials, such as stumps, logs, or light slash. However, there is no fundamental reason why mixtures of fast-growing shade-intolerant species of trees cannot be established to form stratified mixtures with simultaneously established tolerant species as described in Chapter 16. In fact, the intolerant species may act as a nurse crop for the tolerant species.

On most sites, the outcome of direct seeding still depends on rainfall. If climatic records indicate that failures ought to be anticipated, for example, in 1 year out of every 4, the true cost of each successful operation should take this into account. In some regions, the rainfall is so undependable that direct seeding may have to be restricted to sites where the soils remain moist during drought periods.

The chances of success are significantly increased if the seed is treated so that it will be capable of prompt and vigorous germination. This can critically shorten the period of exposure to predators and unfavorable weather. The same seed of mediocre quality that germinates well in the nursery may fail under the more hostile conditions of the wild. Thus, fresh seed with high viability is distinctly preferable to that which has been in cold storage for several years.

Relative Merits of Direct Seeding and Planting

There is much more risk of poor survival with direct seeding than with planting. New seedlings that germinate and grow in the field have scant protection from the numerous lethal agencies that can be controlled in the nursery. Trees established by direct seeding grow no faster than natural seedlings, so they suffer more than planted ones from competing vegetation. Furthermore, there is no opportunity to shorten rotations as there is in planting.

Direct seeding is inherently cheaper than planting because it involves less labor and equipment. It avoids investments in nurseries and the overhead charges involved in their operation. Large areas can be seeded more quickly, on shorter notice, and with fewer organizational problems. The only preliminary step is seed collection, although large quantities are required. The roots of trees established by seeding develop naturally and are not subject to the deformities that are suspected of making planted trees susceptible to windthrow and root rot. Species that develop taproots or distinctly shallow, lateral root systems grow best if their roots develop naturally. Direct seeding is possible on soils where planting is not feasible because of stones, stumps, or other obstructions, but only if the sites are otherwise favorable.

Direct seeding can often be conducted over longer periods than planting, and during colder or wetter weather. The main timing limitations are excessively dry weather or wet conditions on flat ground, a need to minimize the exposure period to seed-eating animals, and avoiding unseasonable germination. Because germination often occurs after older seedlings have broken dormancy, the best time for direct seeding may actually come shortly after the regular planting season, thus enabling continuation of activity even where planting is the standard method of artificial regeneration.

If dense stocking is desirable, it is more economically viable with direct seeding than with planting. However, the risk of localized understocking and overstocking is far greater. Stands established by direct seeding are likely to require more subsequent treatments, such as

re-seeding patches, release cutting, and precommercial thinning, than planted stands.

Broadcast Seeding

The simplest type of direct seeding consists of scattering seeds uniformly over the area to be restocked. This has been termed **broadcast seeding**. This is likely to be a waste of seed unless the conditions of the soil surface and competing vegetation are made appropriately receptive. Broadcast seeding is commonly used to regenerate species adapted to fire. It is essential to expose enough spots of bare mineral soil and to eliminate most preexisting vegetation. Site preparation such as prescribed fire is typically justified mainly as a means of removing vegetation that will ultimately compete with the new crop after it is established.

Broadcast sowing is very rapid, and is most often used when it is necessary to cover large areas quickly. Its most serious drawback is the lack of any provision for covering the seeds. For this reason, it is best done during moist weather. The seeding rates vary considerably depending on the favorability of site and anticipated weather. Recommendations ordinarily call for 10,000–25,000 viable seeds/acre (25,000–62,000/ha), provided that these seeds are treated with appropriate repellents. However, the seeding rate should be carefully adjusted from year to year on the basis of quantitative observations of the results of previous seeding projects.

Most broadcast seeding is done from the air (Panel on Aerial Seeding, 1981). The use of aircraft is usually feasible only if several hundred acres (hectares) or more can be done in a single flight. The uniformity of spreading seeds is possible only if the distributing equipment is closely calibrated by GPS tracking. Fixed-wing aircrafts do a faster and cheaper job than helicopters, but are best adapted to seeding over gentle terrain where the areas to be seeded are large and uniform. Helicopters are more suitable if the terrain is rugged, or if the areas to be seeded are intermingled with those on which seeding is unnecessary or unlikely to succeed. The cost of aerial seeding itself is small compared with that of the seeds, logistical organization, and any associated site preparation. Broadcast seeding can also be done on the ground at rates up to 20 acres (8 ha) per day with crank-operated "cyclone" seeders like those used for sowing grain crops. The cost is about the same as aerial seeding, but it takes much longer to cover a given tract.

Strip and Spot Seeding

Failure in direct seeding is least likely if the seeds are sown in spots or strips that are specially prepared or selected (Fig. 15.10). The sowing itself is more expensive than broadcast seeding, but cheaper than planting. Strip sowing and spot sowing are more economical of seed

Figure 15.10 A stand of longleaf pine in Louisiana established by direct seeding on disked strips. The seedlings are in the middle of the fourth growing season and have been sprayed once with fungicide for control of brown-spot disease. *Source:* Yale School of Forestry and Environmental Studies.

than broadcast sowing, and can be done successfully in a much wider range of times and places.

If the terrain is suitable and there is no need to attempt to eliminate all the competing vegetation, the mechanical preparation of the soil can be accomplished by furrowing or disking in strips. Although the seed is sometimes broadcast on the strips, it is usually much better to take full advantage of the preparatory work and apply the seeds so that they are covered with soil or pressed into it. If the site preparation has left air pockets in the soil, it may be necessary to lightly recompact the soil in the spots or strips to be sown.

Tractor-drawn equipment has been or can be devised to do light soil preparation and to sow and cover seeds individually in one pass of the equipment. Such machines can cover 25–60 acres (10–25 ha) per day on gentle terrain at roughly half the total cost of planting. In preparing spots or strips for the seeds, it is important to manipulate soil surfaces in ways that will prevent soil or litter from being moved by water, ice, or wind in ways that undermine or bury germinating seedlings. Shallow furrows can be plowed to anchor blowing leaves, and ridges can be constructed to deal with poor drainage. Otherwise, it is better to keep the soil surfaces as level as possible to avoid erosional effects.

Spot seeding is limited to operations that are too small to justify use of tractor where steep terrain and obstructions prevent their use. The spots are prepared with hand tools or merely by kicking the debris to the side. It is difficult to arrive at the proper relationship between the spacing of seed spots and the number of seeds applied to each. If one seed is sown on each spot, many spots must be prepared and seeded to allow for all the failures. If enough seed are sown on each spot to ensure that each has one established seedling, some spots will be choked with seedlings. To compromise for either problem, several seeds are sown on each spot, and these are spaced at intervals closer than would be used in conventional planting. It must be anticipated that the stocking of the stand will be erratic and that it may become desirable to thin overcrowded spots and patches.

The seeds can be placed by hand, but various special seeding devices resembling corn planters are much more convenient. The seeding devices require less contact with the seed and enable the sowing of up to 5 acres (2 ha) per person-day. The only other tools specially designed for spot seeding are the dibbles used for planting acorns and other large nuts. These are bars shaped to punch holes into the soil obliquely so that the seeds can be planted on their sides.

Application of Direct Seeding

Broadcast seeding from the air was more common in the 1960s in North America than it has been recently. Planting became more favorable mostly because it provides more economical use of the seed that has been expensively produced in tree-improvement programs.

Where direct seeding works, it can enable swift reforestation of various kinds of barren, devastated areas, especially when done from the air. Direct seeding is often one of the best ways to regenerate species with very small seeds, provided that there are enough microsites with bare mineral soil suitable for their germination. The supply of seed must also be abundant and cheap. This technique is often used for Australian eucalypts, which have seeds so small (300–800/g) that they are coated with clay to facilitate application and ward off insects.

One of these species is southern longleaf pine (Mann, 1970) (see Fig. 15.7). In the past, the stemless, taprooted seedlings had poor planting success because the buds were likely to become buried or excessively exposed by the slightest erosion around them. Direct seeding of longleaf pine can be done by broadcast seeding, preferably with 1 year's growth of grass after prescribed burning. However, most of the planting of longleaf pine is now done with container-grown seedlings, which requires fewer seeds than direct seeding and produces better-quality plants.

Heavy-seeded hardwoods, such as oak, walnut, and hickory, have large taproots that are easily damaged in planting. The best artificial regeneration of these species is obtained by direct seeding, although the control of rodents is still a serious problem. Screens and other physical barriers are usually necessary.

Direct seeding is potentially useful as a low-cost means of establishing advance growth of shade-tolerant, exposure-intolerant species beneath full or partial cover of older trees. The slow juvenile height growth of most of these species delays so much return on planting investment that cheap initial establishment is advantageous. Direct seeding is employed mostly for quick reforestation of large, barren areas, on unusual terrain that is physically difficult to plant but is otherwise favorable, and for rather peculiar species that do not withstand transplanting well. The most serious inherent shortcoming is the need for frequent rain after the sowing of seeds.

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16

The Arrangement, Composition, and Methods of Planting

Introduction

Forest plantations come in all shapes and sizes and can be defined by any number of tree seedlings or saplings that are planted together. Tree plantations have traditionally been thought of as being single-species, single-aged, and arranged in uniform neat rows. However, taken more broadly and more literally, orchards, streets, and agroforestry systems can comprise widely or variably spaced plantations of trees.

This chapter is divided into three parts: (1) concepts of spacing, density and spatial arrangements of plantings; (2) high forest plantations categorized as single-aged, single-species, or single-aged, mixed-species, or all-aged, mixed-species; and (3) low forest plantations categorized as single-aged, single-species, or mixed-species.

The Role of Planting

The establishment of new forests, or the regeneration of old ones, by planting is one of the most costly steps in silviculture. However, these costs vary widely, depending on factors such as labor, capital, nurseries, planting stock, equipment, site preparation, and treatment after planting. The benefits can be very high, and there are plenty of cases in which cost–benefit ratio is higher with planting than any other technique of stand establishment. The least costly kind of planting is where labor costs are low and some devastating event such as fire or agricultural use has created a good level soil, free of competing vegetation. At the other extreme are cases requiring control of aggressive invasive vegetation, hand-planting expensive containerized stock with costly labor, or planting in difficult terrain.

The financial case for planting can seem very dismal when the investment, necessarily made at the very beginning of a rotation, is carried at compound interest to the end. Foresters, landowners, and society in general, exhibit some ambivalence in dealing with this matter. Sometimes the planting of trees seems so satisfying that society evades the problem with various direct or indirect subsidies. Where the workforce, techniques, equipment, and facilities that are necessary for large planting programs have been conscientiously developed, there is often a compulsion to use them to the exclusion of alternative means of regeneration.

If regeneration after timber harvest is required by law or ownership policy, the cost is often counted simply as a cost of the harvest rather than as an investment in the future. It is also common to find that a combination of prompt logging with seemingly expensive planting, is the best way to harvest the old stand and to start a new one.

Sometimes, as with reforestation in previously deforested sites, or in afforestation of sites that have never been forested (at least for a long time), the only decision is whether to undertake the effort. Direct seeding is an option but often not feasible. Similarly, planting can be virtually the only way of starting stands of newly introduced exotics or plants produced in genetic improvement programs. These programs are, in fact, one of the most common reasons for using planting rather than natural regeneration to replace good stands.

A distinction should be drawn between planting for timber production versus the reforestation of devastated areas to prevent erosion and similar kinds of degradation to adjacent lands and waters. Where timber is the goal, priority is given to those areas where planting is most rewarding. Reforesting vacant areas commands priority over replacement of degraded stands, and that, in turn, usually outranks planting to regenerate good stands that already have desirable species. If the objective is protection of soil and water, the first areas treated should be those that are the source of greatest erosion and soil degradation. Planting for wildlife or aesthetic improvement is done first where the prospective benefits are greatest, just as for timber. Planting is the most common means of growing trees that are grown for wood production, fruit, aesthetics, and landscaping.

Most planting is done with conifers, especially in the temperate zone, owing to high demand and short supply of coniferous wood, and because conifers are often easier to plant successfully than angiosperms, especially where grass competition exists. Sometimes the best way to

establish hardwoods on old grassy fields is to grow a rotation of planted conifers first and then depend on adjacent natural seed sources of hardwoods to provide advance growth for the second rotation. However, except for problems with grass, there are no natural barriers against the planting of angiosperms. In the warmer parts of the world, important fast-growing species such as the eucalypts (Jacobs and Metro, 1981), teak, *Gmelina arboraea*, and various multi-purpose leguminous trees are commonly planted (Evans and Turnbull, 2004). Just as with conifers, there are cases in which early-successional angiosperms can be planted on exposed sites to create conditions favorable for establishing advance regeneration of species characteristic of later stages of plant succession, as long as there is a nearby seed source for the establishment of advance regeneration (Parrotta, 1997; Ashton *et al*., 2001).

Most of the discussion so far has been centered on reforestation for timber or soil restoration of degraded areas. Planting for other social values usually requires the same site-treatment considerations, but trees need to be grown at wider or denser spacing for different social services and product desired. Examples of reasons for using wider spacing can be tree form, shade and aesthetics for street trees and urban parks, and for the production of fruits and nuts within orchards. Reasoning for denser and closer spacing can be vegetative thickets for quickly stabilizing eroded river banks and coastal dunes, and dense clonal planting for biomass or leaf production for energy or windbreaks. Dense plantings for biomass production will quickly usurp growing space and shade out any vegetative competition after establishment. Wide spacings for orchards or agroforestry systems will always be wasteful of growing space, necessitating perennial treatment of the groundstory to avoid competition with plantings or to facilitate cultivation of a below-canopy agricultural crop.

Density of Plantings

One advantage of planting is that it gives close control of the initial density and spatial arrangement of the new stand (Drew and Fleweling, 1977; Wilson and Oliver, 2000). There is a tendency to think primarily of how many trees will be needed to achieve early occupancy of the growing space. However, it is better to envision the kind of tree form wanted in the stand late in the planned rotation and to work backward from this goal. The additional question of whether or how the stand may be thinned should also be a consideration in planning the initial arrangement (Lundgren, 1981).

If the trees are planted close together, their crowns and roots will soon close and achieve early full occupancy of the site. Greater stand density will induce small branches, slow diameter growth, a low degree of stem taper, and rapid upward retreat of the bases of the live crowns. The trees may seem to be taller than those of less crowded stands, but this is ordinarily an optical illusion, at least as far as comparing the tallest trees in open stands and dense stands. The height growth of the leading trees of a stand remains the same over a wide range of stand density, but is reduced if stands are extremely crowded or very open. An extremely dense stand would be one for gross biomass. An example of a very open stand would be one within an urban park.

Total production of wood is maximized at the highest stand density that does not cause loss of height growth of the tallest trees. If the stand density is any lower, there will be some loss of potential total production during the delay in achieving full occupancy. Although the rate of production is generally the same after achieving full occupancy, there is no way to recover any production loss from such a delay. However, there would be a purpose in very dense planting to maximize total production only where wood was precious and the labor of gathering it so low that saplings could be harvested profitably for products such as fuelwood and fodder.

If timber production is an objective, the purpose is to optimize the yield of economically utilizable wood. This always involves some specification of a minimum diameter of tree, and because tree value increases rapidly with diameter, the total stand production is deliberately sacrificed to enhance individual tree diameter growth. The greater the diameter objective is, the lower the initial density is. An owner seeking only sawlogs from trees more than 10 in (25 cm) diameter at breast height (DBH) would plant at wider spacing than an owner who could also use pulpwood from trees as small as 4 in (10 cm) from a thinning. The ideal number to plant is the number that can be grown to the smallest size that can be profitably utilized. The question of whether thinnings will be done has bearing on the initial density. If thinnings cannot be made, it is best not to have the stands close any earlier than is essential for the development of acceptable stem quality. Conversely, if early thinnings are certain, it can be desirable to plant more trees to enhance the yield from thinning. There are also other considerations to be made when considering spacing. For example, tree species intended for sawtimber that do not self-prune easily will need to be planted more densely than what would be normal in order to restrict branch size and prevent the trees from tapering too much. Sometimes it is even desirable not only to plant these extra "trainer" trees but also to kill some of them in later precommercial thinnings (see Chapter 21).

The initial density of stands can also be varied with differences in site quality depending upon management objectives. In general, the better the site, the greater is the number of trees that can grow at an acceptable rate.

The crucial variable is the amount of foliage that can be supported by the soil moisture available for growth. Parts of alluvial flood plains that have continuously moist but well-aerated soils are good examples of the sites where trees can be close together but still grow well. At the other extreme, trees planted on dry sites will need to be spaced so far apart that their crowns never close, even though the roots presumably do. In such cases, artificial pruning is sometimes substituted for the natural pruning associated with closed canopies.

Planting density should also vary with species, but so many kinds of factors are involved that no easy generalizations can be made. Theoretically, stands of shade-tolerant species can be denser than those of intolerants because they can carry more foliage. However, considerations such as product objectives, crown form, and cost of planting stock also influence decisions made on planting density. If there is small variability in height growth among trees within a stand, as is the case with red or lodgepole pine, there is a risk that all of the trees will grow slowly and uniformly in diameter, leading to stagnation if there are too many of them. For such species, one might logically plant fewer trees as compared to a species which exhibits enough variability to cause early differentiation into crown and diameter classes such as eastern white pine or black birch. Also, for intensive timber plantations that include the use of superior genetic stock, and in which the understory competition is controlled and the plantings fertilized, the trees will close canopy sooner than with conventional spacing. Landowners in the southern US are planting fewer trees because of the fear that increasing density-related competition between trees will occur at a size class that is pre-merchantable.

Table 16.1 Numbers of trees per unit of area for different approximately equivalent spacings, in traditional and S.I. (metric) systems, with arithmetic perfectly constant only within each system.

Spacing		Number of trees	
Feet	Meters	Per acre	Per hectare
2 × 2	0.6 × 0.6	10,890	27,778
3 × 3	0.9 × 0.9	4,840	12,346
4 × 4	1.2 × 1.2	2,722	6,944
5 × 5	1.5 × 1.5	1,742	4,444
5 × 10	1.5 × 3.0	871	2,222
6 × 6	1.8 × 1.8	1,210	3,086
6.6 × 6.6	2.0 × 2.0	1,000	2,500
7 × 8	2.1 × 2.4	778	1,984
7 × 10	2.1 × 3.0	622	1,587
8 × 8	2.4 × 2.4	681	1,736
8 × 10	2.4 × 3.0	544	1,389
9 × 9	2.7 × 2.7	538	1,372
9 × 10	2.7 × 3.0	484	1,235
10 × 10	3.0 × 3.0	437	1,111

Source: Mark S. Ashton.

Spatial Arrangement of Plantings

Consideration should be given not only to the number of trees to plant but also to their geometric arrangement. The arrangement that normally comes first to mind is the very common method of square spacing. The chief advantage of this arrangement is that it facilitates control of the work of hand-planting crews. It is the only arrangement compatible with driving grass-mowers in straight lines both between and across the rows. Such treatments may be needed in plantations of Christmas trees, and for tree orchards for fruit and nuts.

Square or rectangular spacing does not provide for early development of uniformly closed stands (Table 16.1). However, if the crop or product of the tree is derived from its crown (leaves, fruit, nuts) rather than dependent upon its bole form (sawtimber, latex, sap), then square spacing is appropriate. Square spacing provides uniformly more growing space to individual vigor and growth than other more space-efficient arrangements that encourage stronger competition between individuals. For more uniform closure and earlier crown competition between individual trees, there are two other alternative spacing arrangements. The ideal arrangement is **hexagonal spacing**, in which the tree crowns fit together in the horizontal dimension like hexagons and stand at the corners of equilateral triangles. As the crowns expand, competition is joined uniformly around them and not unevenly as with square spacing. This kind of arrangement requires costly measurements and is seldom used. The **staggered** arrangement is virtually the same and much easier to establish. This involves planting the trees in parallel rows with each tree opposite the middle of the gaps between trees in adjacent rows.

The important aspect of the hexagons and their uniformity of crown coverage is that they are much more crucial in influencing the later stages of stand development than at the beginning. When the stand is planted, the important final crop-trees are mixed with and generally indistinguishable from the more numerous ones that will be thinned out as the stand develops. Any total production lost, because some spots are slowly closed over by trees, is likely to be in the form of small-diameter wood of debatable economic utility. Only as the stand gets older does it become desirable in thinning to

secure uniform coverage and work toward the hexagonal arrangement. The numbers of trees for various spacings and kinds of arrangement are shown in Table 16.1.

Some early mortality will almost always occur, so it is necessary to consider how this might affect the number planted. If it can be anticipated that the losses will be randomly and uniformly distributed, it is then logical to plant enough extra trees to equal the expected loss. However, if the losses tend to occur in patches because of unforeseen differences in soil and microtopography, as is usually true, it is best not to deviate from the optimum spacing. If more trees were planted to allow for patchy losses, the surviving parts of the stand would be too dense and the vacant patches would still be empty. In such cases, the best course of action is to determine whether to fill the gaps by supplementary planting or simply to accept the vacancies. The technical term for supplementary planting is sometimes called **filling in**. Filling in does not work with fast-growing species because the lag time is sufficient to relegate those trees that were planted later to lower crown class positions upon canopy closure.

Regularity of spacing should not be pursued to the exclusion of other considerations. Deviations from the spacing pattern are fully justified if patches of poor soil or competing vegetation can be avoided, or if trees can be placed on the shady sides of obstacles such as stumps or logs. The effect of natural obstacles and mortality among the planted trees always reduces the initial stocking below the figure theoretically indicated by a given interval of spacing and should be taken into account in planning operations. Uneven spacing of trees does cause their crowns to become asymmetrical, and this can occasionally be detrimental. Any associated asymmetry in the stem appears to be most pronounced in the region of the basal butt-swell, whereas the upper part of the stem remains more nearly circular in cross-section.

If trees are planted in furrows such as those created by most planting machines, it is cheaper to have them close together within the rows but with the rows far apart. This reduces the number of times the machine needs to be turned around, as well as the power used to plant a given number of trees. Furthermore, if the rows are far enough apart, it may be much easier to enter the stand with logging machinery at the time of the first thinning, for fertilization or for understory control. In determining the number of trees required for this kind of row planting, it can be thought of as a rectangular spacing even though the placement within the rows is not likely to produce a perfectly rectangular arrangement. If increasing the width of all rows would cause the overall density to be too low, it may be better to have only some of the spaces between rows wide enough for later thinning operations.

Close initial spacing induces better stem form in trees destined for the final crop. However, if the final crop consists of trees 25 ft (8 m) apart, it seems wasteful to plant trees 6 ft (2 m) apart just for the training effects of competition. It could be enough to have clusters of densely spaced trees centered at 25 ft (8 m) intervals with more widely spaced ones between the clusters. The clusters can be planted first and the more widely spaced trees afterward. It is almost mandatory that the clusters be precommercially thinned when the training effects have been accomplished; otherwise, the well-formed central trees are likely to be suppressed by the larger-crowned outer trees. However, because of its administrative complexity, this **cluster** arrangement is seldom used.

High Forest Plantations

High forest plantations can be defined as those plantings of seedlings or artificial seedings that give rise to tall-statured forests that are managed over relatively long rotations or cycles, relative to low forest plantations that are of vegetative origin, short statured, and on short rotations. There are three categories: (1) single-species, single-aged plantations which require shade-intolerant seedling stock that are planted together at a fixed spacing; (2) mixed-species, single-aged plantations which require the selection of seedling stock that are compatible in shade tolerance and intimate growth and that can be planted together at a fixed or variable spacing at one time; and (3) mixed-species, multiple-aged (or all-aged) plantations, including seedling stock of mixed composition and age class.

Single-Species, Single-Aged Plantations

Timber Production and Traditional Reforestation

Almost all tree species that humans have selected for planting on open lands can be considered shade intolerant. Most would be placed in the regeneration guild “pioneers of stem exclusion” (as defined in Chapter 5: Table 5.2, Fig. 5.11). These tree species hold numerous attributes in common. They are fast growing, small seeded, and prolific, requiring mineral soil and sun for best germination. Their crowns are compact, with high rates of photosynthesis and transpiration, and their stems are columnar, monopodial, and straight, with capacity for high diameter increment in bole-wood (Table 16.2). They are ideal species for dimensional timber production, though many of these species have also been used in reforestation for erosion control and watershed stabilization, carbon sequestration, and as a fallow crop on agricultural lands.

Plantations with single species usually require intensive site preparation to eradicate any competing vegetation (see Chapters 7 and 20 for herbicide use). Rotations for timber can be as short as 10 years in southern Brazil with

Table 16.2 A list of timber and pulpwood species and their affiliated taxonomic family commonly used for single-species reforestation and plantation systems. Species are listed with their region/country of planting, climate type, and rotation length. This list accounts for almost 95% of all timber trees in plantations.

Species	Region	Rotation length (yrs)
Acacia mangium (acacia) (Leguminosae)	Pantropical (wet)	7–15
Acacia auriculiformis	Pantropical (wet)	7–15
Cumminghamia lanceolate (Chinese fir)	Subtropical/China (wet)	15–30
Eucalyptus camaldalensis (eucalyptus) (Myratceae)	Pantropical/subtropical (dry)	5–15
Eucalyptus globulis	Pantemperate (wet)	15–20
Eucalyptus urophylla x grandis	Pantropical/Brazil (wet)	10–20
Gmelina arborea (gmelina) (Verbenaceae)	Pantropical (wet)	10–25
Hevea brasiliensis (rubber) (Euphorbiaceae)	Tropical Asia (wet)	15–25
Picea glauca (white spruce) (Pinaceae)	Boreal/Canada	50–60
Pinus caribaea (Caribbean pine) (Pinaceae)	Pantropical (wet)	15–25
Pinus eliottii (slash pine)	Subtropical Americas (wet)	15–25
Pinus patula (patula pine)	Pan-subtropical/montane (wet)	15–25
Pinus radiata (radiata pine)	Pan-subtropical/temperate (wet)	25–35
Pinus sylvestris (Scots pine)	Temperate/boreal/Eurasia	50–120
Pinus taeda (loblolly pine)	Temperate/America (wet)	15–30
Pseudostuga menziesii (Douglas-fir) (Pinaceae)	Temperate/America (wet)	40–55
Populus spp. (cottonwood) (Salicaceae)	Pantemperate/China (wet)	7–20
Swietenia macrophylla (mahogany) (Meliaceae)	Pantropical (wet)	25–35
Tectona grandis (teak) (Verbenaceae)	Pantropical (wet)	20–35

Source: Mark S. Ashton.

Eucalyptus spp. In the southeastern US rotations of loblolly pine on old agricultural lands can be as short as 18–20 years. Spacing has traditionally been at 6 × 6 ft (2 × 2 m) for logistical reasons, but some companies use staggered spacing to more efficiently utilize growing space. Spacing and thinning studies on loblolly pine by Baldwin *et al*. (2000) demonstrated the importance of thinning on tree growth and form, as compared to initial spacing for short rotations (i.e., 25 years). Growth differences among plantations that ranged in spacing between 6 × 6 ft (1.8 × 1.8 m) and 12 × 12 ft (3.7 × 3.7 m) were not as large as growth differences when plantations were heavily thinned. Trees from heavily thinned stands had more cylindrical boles, longer crowns, larger branches, and more overall biomass than unthinned or lightly thinned stands (Baldwin *et al*., 2000).

Spacing trials with Douglas-fir plantings in coastal Oregon, Washington, and British Columbia demonstrated the importance of wide spacings, 13 × 13 ft (4 × 4 m), if you are growing trees for merchantable sawtimber volumes over long time horizons (i.e., greater than 50 years) (Curtis and Reukema, 1970; Reukema, 1970). Few trees reached merchantable sawtimber size at close spacing of 4.3 × 4.3 ft (1.3 × 1.3 m) in sufficient time, and precommercial thinning usually does not justify the costs. Studies of height-to-diameter ratios (H/D) also suggest that trees planted at wider spacings have lower H/D values and are less susceptible to wind damage because of this (Wilson and Oliver, 2000). Results of the same study also suggest that if trees are planted too densely, thinning needs to be done more immediately to lower H/D values, and, if delayed, thinning can be much less effective (Wilson and Oliver, 2000).

Finally, growing plantations for timber usually demands greater heartwood than sapwood. Studies with eucalyptus in Brazil show that tree diameter and heartwood content are proportionally related (Miranda, Gominho, and Pereira, 2009). Wide spacings (13 × 13 ft, 13 × 16 ft) (4 × 4 m, 4 × 5 m) and thinnings will increase diameter growth and thus the proportion of heartwood.

Intensive cultivation of single-species, single-aged plantations dominates the most productive lands on which forestry can be practiced. These plantations have mostly been established on old agricultural lands or from conversion of second-growth forests. They are now sometimes referred to as the wood baskets of their respective countries. These plantations and the species within them are largely responsible for producing the world's construction woods (Table 16.3). One such wood basket is the southeastern US, a plantation region that

Table 16.3 The area extent of the plantation timber producing regions of the world in 2015.

Region	Main countries	Area (ha)
Africa	South Africa/Ethiopia	16,000,000
Asia	Indonesia/China/India	129,000,000
Australasia	Australia/New Zealand	4,400,000
Europe	Scandanavia/Russia	83,000,000
North America	South and Pacific Northwest US	43,000,000
South America	Coastal Brazil	15,000,000
TOTAL		290,400,000

Source: Adapted from FAO, 2016 with permission from FAO.

includes almost half of the world's industrial timber plantations, although the coastal regions of southern Brazil and southern Chile, South Africa, and New Zealand all have higher growth rates and are increasing in area and timber production. In these places, silviculture resembles agriculture. Researchers recognize that both the trees and soils need to be actively managed together over time, starting with improved trees that match the specific site, where the competing vegetation has been suppressed first by tillage and then with applications of herbicide, repeated additions of nutrients, thinning, and pruning (Allen, Fox, and Campbell, 2005).

Interestingly, besides timber trees, other products produced at spacings suitable for timber production also focus on maximizing bole vigor and increment growth rate by carefully balancing the number of individuals per acre while maintaining the vigor and health of the crown. Products such as resins, latex, and saps, like timber, are derived from the bole. As in dimensional timber production, spacing is critical to balance vigor of individual bole-growth increment with maximizing stocking of number of individuals per acre. Examples of tree plantations that produce important resins include many of the hard pines that historically were tapped for a group of products called naval stores (Williams, 1935; Perry, 1968), and in Southeast Asia, resins tapped from *Shorea* in the traditional and ancient Damar tree gardens of Java produce incense for temples (Torquebiau, 1984). Rubber plantations are usually established at a 10 × 10 ft (3 × 3 m) spacing on even ground, but on steep slopes it becomes rectangular, with a 10 ft (3 m) spacing between trees and 23 ft (7 m) spacing between rows that follow the contours. By year 5 they produce a weekly supply of latex and at the end of their rotation (about 25 years) they can be harvested for their timber (Sethuraj, 1987). Also, the best example of tapping for sap is the sugar maple tree that is carefully spaced by thinnings from a naturally established stand that is traditionally called a sugar bush (Koelling and Heiligmann, 1996). There is no reason not to establish a sugarbush plantation but the species is slow growing and the cost of waiting not worthwhile if you can take advantage of naturally established older stands.

Figure 16.1 An example of a taungya plantation. A 2-year-old *Dipterocarpus* plantation in Vietnam with vegetables cultivated on the ground and small trees of banana and papaya interplanted amoung the *dipterocarpus* trees. *Source:* Mark S. Ashton.

An old colonial management technique in cultivating timber in a plantation and at the same time accommodating the production of agricultural crops for villagers at the start of the planting is called "taungya" (Champion and Seth, 1968; Joshi, 1980; Wiersum, 1982) (Fig. 16.1). Developed in the late 1800s by the British in Myanmar (Burma) as a way to provide for the needs of the local people and provide teak for the rail roads being constructed across India, it is now a system that has merit in many places. Villagers would be responsible for keeping the planted trees weed-free during the few years that they cultivated, and after canopy closure and the shade decreased their crop yields, they would move to another newly planted site. What had been adopted was a simplified analog to the indigenous swidden systems of the region.

Widely Spaced Planting Systems

Many plantations are focused on producing things other than timber, such as latex or sap from the stem. Widely spaced single-species, single-aged plantations are not focused on balancing efficiency of growing space between individuals and stand-level productivity. Widely spaced plantings, relative to the size at maturity of the trees, are focused on allocation of growing space almost entirely to ensuring the full crown expansion for growth and production of individuals. These systems are thus concerned with producing products or services dependent upon individual crown vigor and form. Trees that bear fruits and nuts from the outer branches such as apples, cherries, citrus, mangos, almonds, pecans, and avocados are all examples of wide spacing. However, another very different example of a widely spaced planting is that of street trees or trees planted in open parks for their crown form, shade, and color. Finally, widely spaced plantings can be a compromise between producing a product or service from the tree, and producing another agricultural or fodder crop beneath. Silvopastoral systems would be considered an example of this, and there are many agroforestry systems where trees are interplanted for provision of partial shade, and to improve soil fertility for cultivation of crops.

Silvopastoral and Agroforestry Systems

Silvopastoral systems are examples of combined values producing timber, shade for livestock, and fodder. This is an important combination in many regions of the world. Spacing studies in the southeastern US with loblolly pine showed that herbage yields of tall fescue grass increased with wider spacings of trees but its mineral nutrition declined. Spacings of loblolly pine for acceptable grass yields had to be at least 16 × 16 ft (5 × 5 m) (Burner and Brauer, 2003). Similarly for pine silvopastoral systems in New Zealand, satisfactory pasturage was secured around a spacing of 23 × 23 ft and a final stocking of 80 trees/acre (7 × 7 m, 200 trees/ha), though a lower stocking of 40 trees/acre at a 33 × 33 ft spacing (100 trees/ha, 10 × 10 m), can facilitate pasture yield well into the rotation, but pasture quality declines with increased needle cover (Hawke, 1991). In the tropics, common trees that are planted with grasses are large leguminous trees that can also fix nitrogen, and provide nutritious edible pods that the cattle can eat. One such common tree in Latin America is *Albizia saman*, a tree that can be planted at 260 × 260 ft (80 × 80 m) because of its crown diameter at maturity of 130 ft (40 m).

Similar spacings in silvopastoral systems can be used within agroforestry systems where the widely spaced trees are 23 × 23 ft (7 × 7 m) and even greater, and are used to provide shade for agricultural crops planted beneath (Beer, 1987). Many leguminous trees are also used to enrich the soil with nitrogen (e.g., *Erythrina* spp., *Inga* spp., *Gliricidia sepium*) (Beer, 1987). The kinds of agricultural crops best suited to be cultivated beneath widely spaced nurse trees are annual grains and vegetables (Table 16.4; Fig. 16.2).

Orchard Systems

In orchard systems, fruit and nut trees can be categorized into two kinds of growth forms. First, there are canopy trees that have strong monopodial forms. Two examples of fruit trees with this kind of growth form are the tropical forest canopy fruit trees durian (*Durio zebithinus*) and jak (*Artocarpus heterophylla*). The only need for these kinds of fruit trees is to be provided plenty of growing space, often in mixtures with other trees because many are relatively later successional species and exhibit density dependence, and no pruning is necessary. These kinds of trees grow well in high forest plantations with other species (see section on mixed-species plantations). However, most fruit and nut trees have strong branching growth forms with rounded crowns in which a balance has to be obtained, usually through pruning and spacing, between branch growth and fruiting (Verheij, 1986). This group can be considered shade intolerant and early successional. The best examples of this are with the Rosaceae tree family (apples, plums, peaches, pears, plums, and cherries) (Fig. 16.2). Spacing in orchard systems is regulated to ensure full growing space occupancy of individual trees at maturity. Size of varieties can dictate initial spacing from fully dwarf varieties 8 ft (2.5 m) high, to dwarf varieties 13–16 ft (4–5 m), to traditional varieties 20–26 ft (6–8 m). Smaller-statured trees allow for easier access for pruning and picking, and closer spacing, resulting in more trees per acre/hectare. Spacing is usually in rectangular rows. Depending upon size at maturity, spacing may be as small as 3 × 10 ft (1 × 3 m) or as large as 32 × 32 ft (10 × 10 m) (Robinson, 2003). Many varieties are now trained and supported with trellises and postwork.

Street Trees and Parklands

Trees to be planted in urban environments have several universal characteristics. They are tolerant of pollutants and soil compaction, and are able to withstand confined spaces for rooting and crown growth. Many of the selected species come from seasonally inundated floodplains. Common street trees planted in North America from this kind of ecosystem are pin oak, sycamore, and silver maple. In the tropics, the ubiquitous Indian almond (*Terminalia catappa*) is a tree that can be found in almost every tropical city.

To select a tree species for planting, there is a hierarchical series of considerations that need to be met. Trees should be selected first based on their hardiness and abilities to meet the conditions of the planting site. Second, trees should be selected for their growth and form for the growing space available. Only then should a

Table 16.4 Common tree species found in silvopastoral, agroforestry, and fruit and nut orchard systems. For silvopastoral and agroforestry systems, tree species are listed by legumes and non-legumes along with their region of planting and climate type (wet versus dry/arid; tropical versus temperate). Note that for agroforestry systems in dry or temperate climates, there are no common or widespread tree crops but many nurse tree species. In these climates most agroforestry crops are annual or seasonal food plants that can avoid the dry/winter seasons.

TROPICAL		
Silvopastoral	**Family**	**Region of influence**
	Legumes	
Acacia albida		Africa (dry)
Acacia nilotica		South Asia (dry)
Albizia guachapele		Central America (wet and dry)
Dalbergia sissoo		South Asia (dry)
Diphysa robiniodes		Central America (wet)
Dipterix panamensis		Central and South America (wet)
Pithecellobium saman		Central and South America (wet and dry)
Prosopis juliflora		Central and North America (arid)
	Non-legumes	
Guazuma ulmifolia	Malvaceae	Central and South America (wet and dry)
Spondias spp.	Anacardiaceae	Central and South America (wet and dry)
Terminalia Amazonia	Combretaceae	Central and South America (wet and dry)
Agroforestry	**Family**	**Region of influence**
Crop trees	Non-legumes	
Camelia sinensis (tea)	Teaceae	South Asia, China, Kenya (wet)
Coffea Arabica (coffee)	Rubiaceae	Andes, South America, Central America (wet)
Elettaria cardamom (cardamom)	Zingerbaceae	South Asia (wet)
Theobroma cacao (cocoa)	Sterculiaceae	West Africa, South America (wet)
Nurse trees	Legumes	
Acacia albida		Africa (dry)
Calliandra calothyrsus		Pantropical (wet)
Erythrina poeppigiana		Pantropical (wet)
Gliricidia sepium		Pantropical (wet)
Inga edulis		Central and South America (wet)
Leucaena leucocephala		Pantropical (wet)
Sesbania sesban		Pantropical (wet)
	Non-legumes	
Gmelina arborea	Verbenaceae	Pantropical (wet and dry)
Grevillea robusta	Proteaceae	Pantropical montane (wet)
Orchards	**Family**	**Region of influence**
	Legumes	
Tamarindus indica (tamarind)		Pantropical (wet and dry)
	Non-legumes	
Anacardium occidentale (cashew)	Anacardiaceae	Pantropical (wet and dry)
Carica papaya (papaya)	Caricaceae	Pantropical (wet and dry)

(Continued)

Table 16.4 (Continued)

Orchards	Family	Region of influence
Citrus spp. (oranges, lemons, limes, grapefruit, pomelos)	Ruaceae	Pantropical (wet)
Cocos nucifera (coconut)	Palmae	Pantropical (coastal)
Elaeis guieensis (oil-palm)	Palmae	Pantropical (wet)
Hevea brasiliensis (rubber)	Euphorbiaceae	Asia, South America (wet)
Litchi chinensis (lychee)	Sapindaceae	Asia (wet)
Mangifera indica (mango)	Anacardiaceae	Pantropical (wet)
Musa spp. (banana)	Musaceae	Pantropical (wet)
Nephellium (rambuttan)	Sapindaceae	Asia (wet)
Persea americana (avocado)	Lauraceae	Pantropical (wet)
Psidium guajava (guava)	Myrtaceae	Pantropical (wet)
Punica granatum (pomegranate)	Bignoniaceae	Pantropical (dry)
Zizyphus jujuba (jujuba)	Rhamnaceae	Asia (dry)
TEMPERATE		
Silvopastoral	**Family**	**Region of influence**
	Legumes	
Albizia julibrissin		Europe (dry)
Gleditsia triacanthos (coffee tree)		North America (wet)
Robinia pseudoacacia (black locust)		North America (wet)
	Non-legumes	
Castanea sativa (sweet chestnut)	Fagaceae	Europe (wet and dry)
Fagus sylvestris (beech)	Fagaceae	Europe (wet)
Juglans nigra (walnut)	Juglandaceae	North America (wet)
Pinus elliottii (slash pine)	Pinaceae	North America (wet)
Pinus radiata (radiata pine)	Pinaceae	Australasia (wet)
Pinus ponderosa (ponderosa pine)	Pinaceae	North America (dry)
Quercus ilex (holme oak)	Fagaceae	Europe (dry)
Quercus peduculata (sessile oak)	Fagaceae	Europe (wet)
Quercus suber (cork oak)	Fagaceae	Europe (dry)
Agroforestry	**Family**	**Region of influence**
	Non-legumes	
Carya illinoensis (pecan)	Juglandaceae	North America (wet)
Castanea spp. (chestnut)	Fagaceae	Pantemperate (wet and dry)
Juglans nigra (black walnut)	Juglandaceae	North America (wet)
Morus spp. (mulberry)	Moraceae	Asia (wet)
Populous spp. (cottonwood/poplar)	Salicaceae	Pantemperate (wet)
Orchards	**Family**	**Region of influence**
	Non-legumes	
Carya illinoensis (pecan)	Juglandaceae	North America (wet)
Castanea sativa (sweet chestnut)	Fagaceae	Europe (wet and dry)

Table 16.4 (Continued)

Orchards	Family	Region of influence
Corylus americana (hazelnut)	Betulacaeae	Pantemperate (wet)
Diospyros kaki (persimmon)	Ebenaceae	Asia (wet)
Juglans regia (English walnut)	Juglandaceae	Pantemperate (wet)
Malus spp. (apples)	Rosaceae	Pantemperate
Olea europaea (olives)	Oleaceae	Eurasia (dry)
Phoenix dactylifera (date)	Palmae	Eurasia (dry)
Prunus spp. (plums, apricots, peaches, cherry)	Rosaceae	Pantemperate (wet and dry)
Prunus dulcis (almonds)	Rosaceae	Pantemperate (wet and dry)
Pyrus spp. (pears)	Rosaceae	Pantemperate (wet and dry)

Source: Mark S. Ashton.

(a)

(b)

Figure 16.2 **(a)** A tropical silvopastoral system in Costa Rica with *Samanea saman*. *Source*: Centre Tecnologic Forestal de Catalunya. Reproduced with permission from Centre Tecnologic Forestal de Catalunya. **(b)** A temperate silvopastoral system in Argentina with *Pinus taeda* (loblolly pine). *Source*: B. Chezdoy, Cornell Cooperative Extension. Reproduced with permission from B. Chezdoy.

(Continued)

(c)

(d)

Figure 16.2 (Continued) **(c)** Alley cropping with recently pruned *Inga* sp., a nitrogen-fixing tree, with corn planted in between rows in Honduras. *Source:* Reproduced with permission from The Inga Foundation. **(d)** Irrigated almond orchard in the Central Valley of California. *Source:* Mark S. Ashton.

tree species be selected for its aesthetic attributes. In the end, there are relatively few trees that meet all these constraints and many of these species are widely planted across both temperate and tropical realms (Table 16.5). Planting considerations within urban open space generally are extremely variable, but tree spacing along streets should be at a width that is suitable when the tree reaches maturity.

Mixed-Species, Single-Aged Plantations

Although most plantations are single-species stands, there is no fundamental reason why they cannot be mixtures of species. It is more complicated to create and manage mixed plantations, but the benefits can outweigh the complexities. However, in a review by Kelty (2006), there are some advantages to mixed-species plantations that include higher stand productivity in both complementary and facilitative interactions: complementary resource use between species that develop stratified canopies, and facilitative improvement in nutrition of tree species growing in mixtures with nutrient-enriching species. These mixtures can increase economic return by greater individual-tree growth rates and improved form. Mixtures can also provide multiple commercial or subsistence products. Finally, complex mixtures comprising many species can be used for restoration of degraded lands and stabilization of eroded watersheds. Large numbers of species of different successional stages planted together can eliminate the need for a series of sequential plantings.

Ecological Theory Behind Mixtures

There is a strong rationale for planting mixtures when single-species plantations are susceptible to insects, disease, or some other kind of disturbance. This is an obvious risk-averse strategy when considering ecological factors of reforestation for conservation and restoration. It is particularly appropriate if one does not have the technical knowledge of what to plant where. Planting or direct seeding a mixture of species will assume that at

Table 16.5 A list of commonly planted temperate street tree species in North America and their site tolerances, characteristics, and stature at maturity.

Species	Site tolerances, unique characteristics, and stature (height)
Small ornamentals	
Amelanchier spp. (serviceberry)	Tolerant of waterlogging and shade, 15–25 ft (4.5–7.5 m)
Acer ginnala (Amur maple)	Brilliant fall foliage, 15–20 ft (4.5–6 m)
Carpinus caroliniana (American hornbeam)	Tolerant of compaction, 15–25 ft (4.5–7.5 m)
Crataegus spp. (hawthorn)	Tolerant of salt and drought, 15–25 ft (4.5–7.5 m)
Lagerstroemia spp. (crepe myrtle)	Showy flowers, 10–15 ft (3–4.5 m)
Prunus cerasifera (purple leaf plum)	Showy flowers and foliage, salt-tolerant, 15–25 ft (4.5–7.5 m)
Pyrus calleana (Callery pear)	Showy flowers and foliage, salt-tolerant, 15–25 ft (4.5–7.5 m)
Syringa reticulata (Japanese tree lilac)	Showy flowers, 25–30 ft (7.5–9 m)
Large to medium shade trees	
Acer campestre (field maple)	Shade tolerant, 35–40 ft (9–12 m)
Acer rubrum (red maple)	Brilliant fall foliage, long-lived, 35–50 ft (10.5–15 m)
Gingko biloba (gingko)	Only male trees are planted to avoid fruit, 40–50 ft (12–15 m)
Gleditsia triacanthos (honey locust)	Fall color, light shade, 50–100 ft (15–30.5 m)
Liquidambar sytraciflua (sweetgum)	Tolerant of waterlogging, compaction, drought, 60–70 ft (18–21 m)
Quercus bicolor (swamp white oak)	Tolerant of waterlogging, 50–70 ft (15–21 m)
Quercus macrocarpa (bur oak)	Drought tolerant, 40–70 ft (12–21 m)
Quercus palustris (pin oak)	Tolerates compaction and pollution, 50–80 ft (15–24 m)
Platanus x acerfolia (London plane tree)	Tolerates compaction and pollution, long-lived, 70–100 ft (21–30.5 m)
Taxodium disticha (bald cypress)	Tolerates flooding, salt, 40–60 ft (12–18 m)
Tilia cordata (little-leaf linden)	Tolerates pollution, salt, 50–60 ft (15–18 m)
Zelkova serrata (Japanese zelkova)	Tolerant of drought, wind, and pollution, 30–40 ft (9–12 m)

Source: Mark S. Ashton.

least some will establish and grow. An example of this reforestation strategy is practiced in Brazil, where a mixture of seed is gathered from the native forest nearby, cleaned, mixed in a slurry, and tilled into old degraded pastures of the Brazilian cerrado when the rains arrive. However, the same is true for economic values. The more prone a single-species plantation is to disease and pestilence or to some climatic variable (drought, wind damage), the more the forester should be thinking about diversifying the investment in the land with other crops. Also, the longer the wait for a rotation of late-successional timber, the greater the potential of incorporating other complementary species and products that can add value to the plantation and diversify the market risk, so that all is not lost at the end of the rotation at the time when the market value for the timber is low.

There are two major ecological considerations for mixtures: (1) density dependence, where related trees do better planted further away from each other; and (2) compatibility (facilitative or complementary), where unrelated trees can benefit or are at least compatible with each other's growth morphology and physiology.

Density dependence has been shown to be an important phenomenon in many tropical forests. Species establish and do better away from the parent tree because they are less susceptible to their host-specific insects and diseases when surrounded by unrelated trees that are inhospitable to those insects and diseases (Wright, 2002). This is one theory as to why tropical forests are so diverse and gives cause to wonder about all those single-species plantations that are busy being established in the tropics around the world. The Asian rubber industry would shudder if the native leaf-rust diseases from the tree's home country, Brazil, ever took a serious foothold in Malaysia or Indonesia (Edathil, 1986). The best example of density dependence for a timber tree is the mahogany family (*Swietenia* spp., *Cedrella* spp., *Entandrophragma* spp., *Toona* spp.). This important timber tree family is susceptible to species of *Hypsophila* moth that are attracted to the terminal leaders of young

saplings. If planted in mixture with unrelated but compatible species, rates of infection can be greatly reduced (Newton *et al*., 1993). There are many more examples of such phenomena that should be taken more seriously than in the past.

In most situations, plants are competing for the same resource and growing space. Plants that compete for the same resource can be very compatible (complementary) with each other if selected carefully. The best example is to take advantage of the disparity in tree growth between seedlings of quick-growing, shade-intolerant species, and seedlings of shade-tolerant species that begin growth more slowly. The fast growers form an upper stratum and, if they are sufficiently far from each other, grow as rapidly in diameter as if they had been heavily thinned. The slower starting ones stay in the lower stratum and there they fill the remaining growing space and usually retain the capacity to grow rapidly once the overstory species have ceased rapid growth and have been removed. One study by Haggar and Ewel (1997) that carefully examined these relationships involved three species of tropical trees and two understory monocots. Results showed the deciduous species to be stratified above the canopy of the evergreen and the evergreen to have deeper fine roots (Haggar and Ewel, 1997; Menalled, Kelty, and Ewel, 1998). This is an excellent example of competitive compatibility.

Several studies have investigated whether compatible mixtures have increased biomass. The earliest example was an investigation into *Larix decidua* with *Fagus sylvatica* and *Picea abies* in Germany (Assmann, 1970). Since then there have been studies that have reported compatible mixtures that showed increased biomass productivity as compared to either species in monoculture (Table 16.6)

There are also facilitative interactions among tree species. Research is demonstrating that this is a more common phenomenon than once thought (Binkley and Giardina, 1998; Wright, 2002). Known facilitative interactions can be categorized into two types: (1) shade tolerance, and (2) soil fertility. Usually these interactions benefit one species while the other is not affected.

There are some great examples for timber plantations where the nitrogen-fixing *Albizi*a tree increased the growth and productivity of *Eucalyptus* in Hawaii and Puerto Rico (Binkley *et al*., 1992; DeBell, Cole, and Whitesell, 1997). The actual combination of both species had a higher biomass yield than any spacing density of either species as a monoculture (Fig. 16.3), and that the tree mixtures with nitrogen-fixing trees accumulate more carbon belowground than mixtures without nitrogen-fixing trees (Binkley, Giardina, and Bashkin, 2000; Resh, Binkley, and Parrotta, 2002). Some species combinations may have direct transfer of nitrogen and other nutrients between tree species by sharing the same ectomycorrhizae (Simard *et al*., 1997). Interestingly, facilitative interactions can also benefit single-species tree plantations through the use of nitrogen-fixing groundcovers. It has been known for many years that planting crops with nitrogen-fixing groundcovers can dramatically increase yields. For example, rubber trees planted with *Calopogonium muconoides*, *Centrosema pubescens*, or *Pueraria phaseoloides* increase latex production by over 4 t/acre (9.8 t/ha) after 20 years of tapping. There is a strong legacy effect because the groundcovers are usually shaded out by year 6, but yields remain high (Broughton, 1976).

Examples of increased facilitatory growth and productivity using shade is evident in between early-successional trees that provide the partial canopy shade for shade-tolerant understory species cultivated in plantations. Current examples of understory trees and shrubs that benefit from shade are cacao (*Theobroma cacao*) and cardamom (*Elettaria ensal*). Growth rates and crop yield are significantly lower when grown in the open. Coffee (*Coffea aribica, C. canephora*) and tea (*Camelia sinensis*) were once solely cultivated with shade trees until sun-loving cultivars were developed.

Choosing Mixtures in Single-Aged Systems

Choosing mixtures for even-aged plantation systems should mean emulating the initial floristics, where trees are chosen for their successional compatibility in shade tolerance and soil resources over time. There are many examples of successional compatibility but actually very few examples of their implementation (see Table 16.6). Part of the reason for a failure to see mixed species more commonly planted is the level of sophistication needed to carefully select compatible species and the economic costs *versus* the perceived benefits that mixtures could yield as compared to a fast-growing, single-species stand. The advantage of mixed-species plantations is an ability to carry to rotation the shade-tolerant and/or density-dependent late-successional tree species that produce luxury furniture, flooring, and artisanal values. The disadvantage is that these very plantations are competing to produce the same products from the very same tree species that are being more cheaply exploited from natural forests across the world, under circumstances where the true cost of their replacement is often ignored.

Spacing in these systems can be very complicated given the different growth rates and crown-to-bole-diameter relationships of different species (Menalled, Kelty, and Ewel, 1998). The most logical approach is to think about the development of an even-aged, second-growth forest mixture which usually establishes with dense numbers of pioneers that self-thin rapidly among themselves. This allows the slower-growing, longer-lived species to attain the canopy to expand their crowns outward and to often stagnate in growth if too many are

Table 16.6 A list of compatible species mixtures for some temperate and tropical forest regions by shade tolerance, successional status, and suggested complementary and facilitative interactions (Binkley, 1983; Binkley *et al*., 1992; Forrester, Bauhus, and Cowie, 2005; Laclau *et al*., 2008; Kelty, 1992; Parrotta, 1999).

TEMPERATE COMPLEMENTARY MIXTURES		
Shade intolerant	**Shade tolerant**	**Main mechanism**[1]
Larix decidua (European larch)	*Fagus sylvatica* (European beech)	Phenology
Larix decidua (European larch)	*Picea abies* (Norway spruce)	Phenology
Picea abies	*Abies alba* (silver fir)	Shade tolerance
Pinus densiflora (Akamatsu)	*Chamaecyparis obtusa* (Hinoki)	Rooting
Pinus strobus (eastern white pine)	*Picea abies*	Rooting
Pinus sylvestris (Scots pine)	*Picea abies*	Rooting/shade tolerance
Pinus sylvestris (Scots pine)	*Fagus sylvatica*	Rooting/shade tolerance
Pseudotsuga menziesii (Douglas-fir)	*Tsuga heterophylla* (western hemlock)	Shade tolerance
Populus deltoides (cottonwood)	*Quercus nutalli* (Nuttall oak)	Shade tolerance
Populus spp. (cottonwood/aspen)	*Picea glauca* (white spruce)	Phenology
Quercus pedunculata (sessile oak)	*Fagus sylvatica*	Shade tolerance/rooting
Quercus rubra (northern red oak)	*Tsuga canadensis* (eastern hemlock)	Phenology
TEMPERATE/SUBTROPICAL FACILITATIVE MIXTURES		
Shade intolerant	**Shade tolerant**	**Main mechanism**[2]
Albizia falcataria (Molucca albizia)	*Eucalyptus saligna* (blue gum)	Nitrogen fixation
Alnus rubra (red alder)	*Pseudostuga menziessii* (Douglas-fir)	Nitrogen fixation
Eucalyptus grandis (rose gum)	*Acacia mangium* (mangium)	Nitrogen fixation
Eucalyptus globulis (blue gum)	*Acacia mearnsii* (black wattle)	Nitrogen fixation
Eucalyptus robusta (swamp mahogany)	*Leucaena leucocephala* (leucaena)	Nitrogen ixation
Robinia pseudoacacia (black locust)	*Quercus rubra* (northern red oak)	Nitrogen fixation

1) Explanations of main mechanism for compatibility: phenology – a deciduous overstory shade-intolerant species allows the evergreen to assimilate carbon at times of the year when the overtopping deciduous tree is leafless; rooting – shade-intolerant species usually has a deeper root system than the more lateral/superficial rooting system of the shade-tolerant, thereby partially avoiding competition for water uptake; shade tolerance – all species mixtures differ in their shade tolerance to insure some degree of compatibility but when listed it is emphasized as the main mechanism for compatibility.
2) Almost all the work that has shown actual increases in productivity in mixture has been related to nitrogen fixation. Evidence suggests there are other facilitative mechanisms through symbiotic relationships with mycorrhizae that can act to supplement other nutrients from the host species to other tree species (e.g., P, Mg) and the process of density dependence, where certain species susceptible to insects and disease can increase in growth when grown in mixture with unrelated (non-susceptible) species.

Source: Data from Kelty, 2006.

competing for the same growing space (Figs. 16.4, 16.5). More species of stem exclusion than canopy dominants allow the plantation to self-thin. Early-successional species can be planted at small spacing, with late-successional species intimately planted at a wider spacing given crown expansion at maturity.

Our understanding of mixtures and successional compatibility appears to run counter to some of the most traditional mixed-species plantation models in Europe. For example in the Spessart region of Bavaria, Germany, it is customary to sow oak acorns at very dense plantings along with some beech and the understory tree *Carpinus betula* (hop hornbeam) (Fig. 16.6) (von Lupke, 1998). However, the different species are kept in the same canopy stratum. This requires careful attention to removing the trees that race ahead and encouraging those that would lag behind in nature. It can also be done by planting different species (e.g., the understory *Carpinus* spp.)

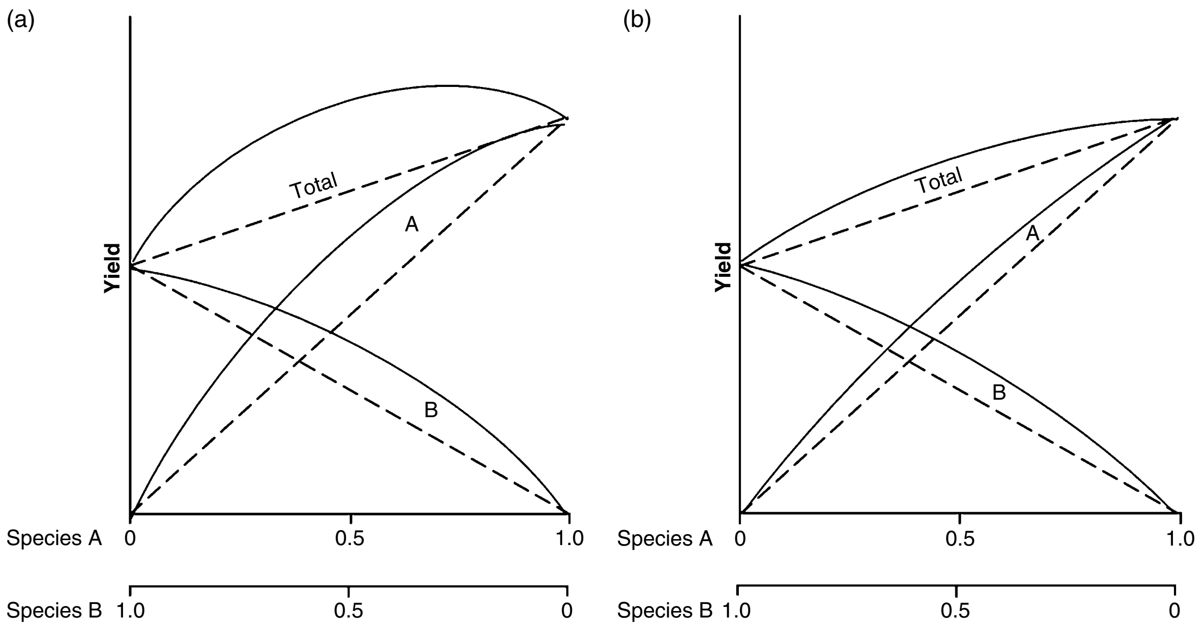


Figure 16.3 The theoretical concept between facilitative and complementary interactions in growth and yield among tree mixtures. **(a)** Facilitative interactions are when two species are intimately mixed in a certain proportion, and productivity is actually higher than if either species were planted alone. **(b)** Complementary interactions are when one species is complemented by a second to increase productivity, but not above the productivity and growth for the more productive species. *Source:* **(a, b)** Mark S. Ashton.

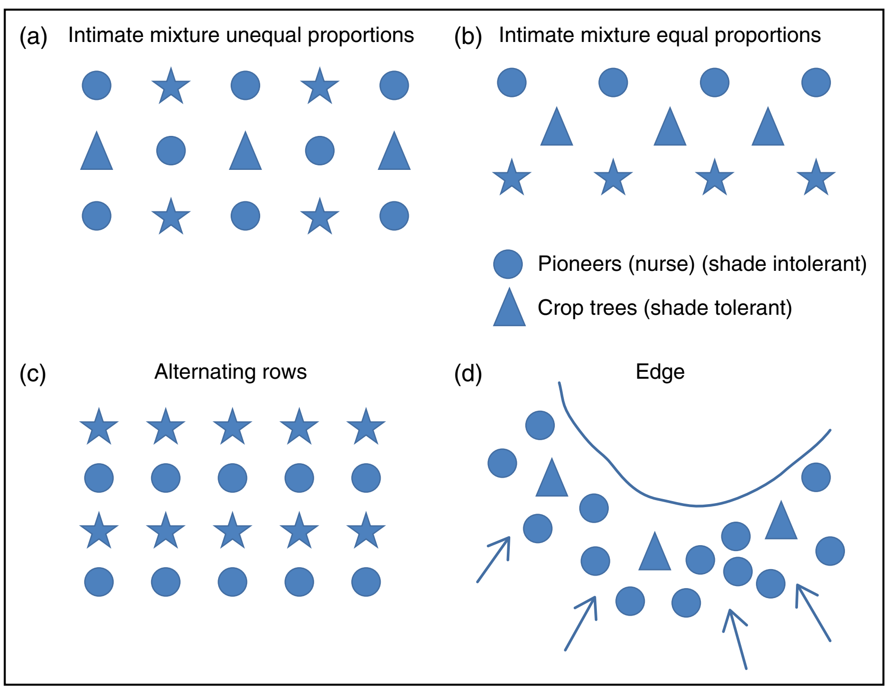


Figure 16.4 An example of different spacing combinations and arrangements for simple and complex mixtures, successionally compatible to maximize efficiency of use of soil nutrients and soil moisture, and the use of plantings to stabilize edges that are susceptible to winds and flooding. *Source:* Mark S. Ashton.

in later years, to purposely shade the boles of the canopy trees and reduce their propensity to release epicormic sprouts. All of this is an attempt to regulate the growth of the oak to very uniform but very small growth rings. Needless to say, it takes over 250 years to achieve harvestable rotations of oak. Although fascinating and a tradition that is largely restricted to the "forestry museum," such a product could have been obtained with oak grown on an 80-year rotation, if allowed to grow uniformly but with wider rings, in intimate mixture with a shade-intolerant birch, a species that would continuously self-thin as oak grew out to replace it.

Planting mixtures of the same successional stage can work when shade-intolerant species are intimately mixed together, but does not work when only shade-tolerants are in the mixture. This is largely because

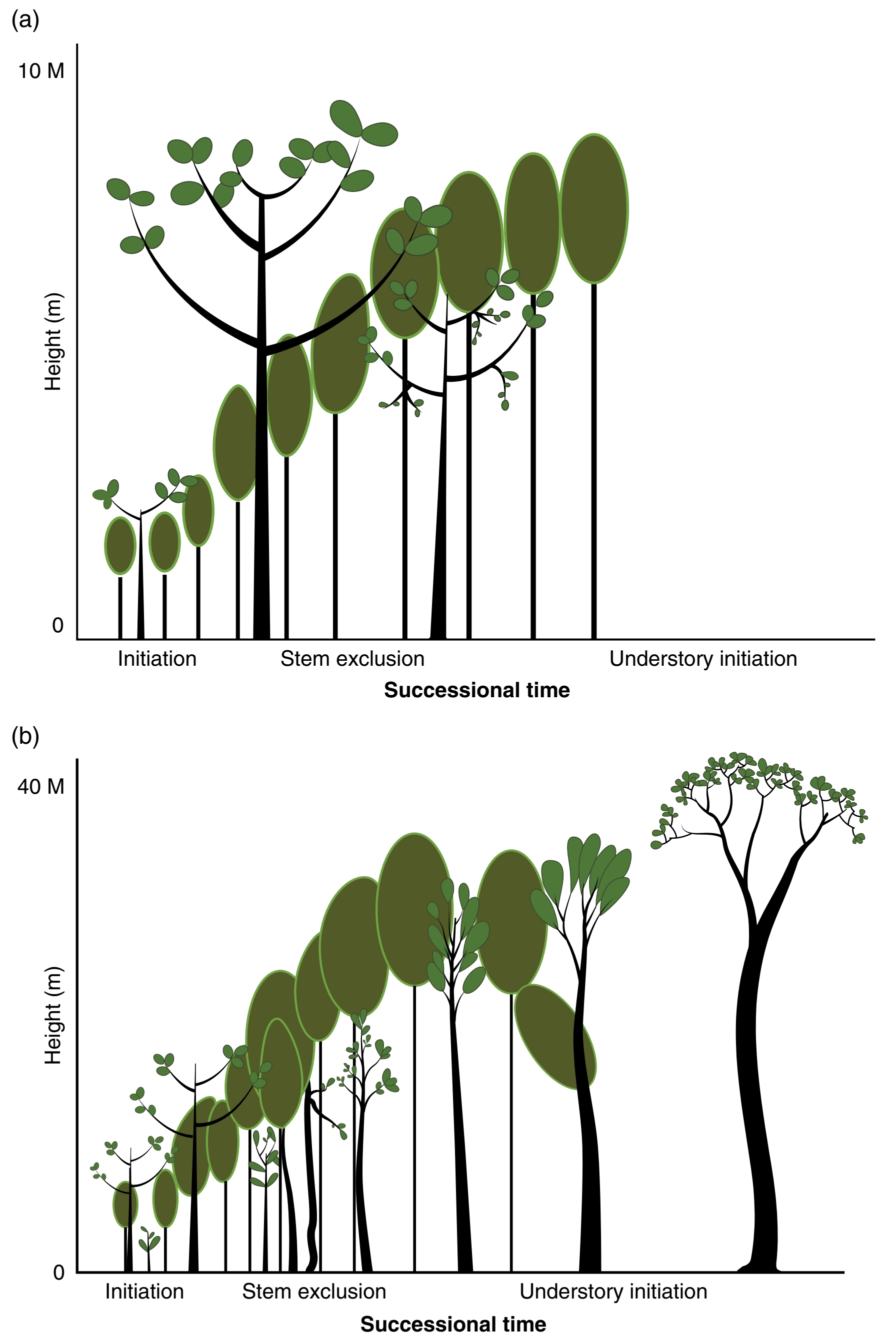


Figure 16.5 Graphic examples of change in crown morphology over time, when late successional trees are planted in mixture with an early successional species. **(a)** Crown morphology changes of a short-lived pioneer tree (e.g., macaranga, pin cherry, sumac) during the initiation stage and as it is overtopped by long-lived pioneers (e.g., birch) during stem exclusion. **(b)** Crown morphology changes of a late-successional tree (e.g., oak) as it grows below short-lived pioneers during the initiation stage and through the long-lived pioneers during understory initiation. Ten meters is equal to about 33.3 ft. *Source:* **(a, b)** Mark S. Ashton.

shade-tolerants can withstand the shade when over-topped by an adjacent competitor and persist for years, before relinquishing its growing space to its equally shade-tolerant neighbor. This does not bode well for fast growth but instead leads to plantation stagnation. Shade-intolerant species will more readily die when over-topped by their neighbors, allowing plantation growth to continue. This phenomenon can be enhanced when selected for shade-intolerant, fast-growing species, some of which fix nitrogen and some that do not (Fig. 16.7). However, there is evidence that conditions for litter decay and microorganisms in spruce forest are effectively counteracted when beech is in mixture, which may prove beneficial for growth (Albers *et al.*, 2004).

Finally, the nature of cluster plantings should be mentioned. Mixed-species, single-aged plantations can be created by planting small, pure clumps so that interactions between species are facilitatory in extent. This is often done on the edge environments of alpine, coastal, or riparian sites where winds and waters can greatly effect the successful initial establishment of trees that are intended to eventually stabilize these sites. Nurse shrub

Figure 16.6 A 25-year-old Spessart oak mixed planting, Germany. Acorns were planted at 12,140/acre (30,000/hectare) with some beech. The plantation has been carefully released at periodic intervals by taking out beech that grew faster than the best oak saplings, and removing oak saplings that were over-topped. *Source:* Mark S. Ashton.

species that are hardy to winds or floods can be planted around the tree plantings as a temporary nurse to promote their establishment.

Mixed-Species with All-Aged or Multiple-Aged (Two- or Three-Aged) Systems

Mixed-species plantations can range in age-class structure between very complex all-aged stands (greater than four age classes) to just two age classes. In this text, two aged is defined as a form of multiple aged; and multiple aged is where there are at least two age classes, usually three. There are many examples of plantations with two age classes, most of which are spontaneous rather than intentionally designed. A major example of this spontaneity is the

Figure 16.7 A 2-year-old single-aged mixed-species experimental trial within the Panama Canal Watershed comprising shade-intolerant nitrogen-fixing legumes (*Dipteryx panamensis*, *Schizolobium amazonicum*) and other shade-intolerant tree species (*Anacardium excelsum*, *Pachira quinata*) in intimate mixture. *Source:* Mark S. Ashton.

recruitment of natural regeneration beneath single-species, single-age, pine plantations of the eastern US. In fact, much of the pine has since been removed, releasing native second-growth hardwood forests. This ability of certain plantation tree species to allow establishment of regeneration beneath, has been been commonly reported elsewhere, particularly in tropical reforestation. Studies on *Acacia mangium* plantings in Indonesian Borneo (Kuusipalo *et al*., 1995; Otsamo, 2000; Norisada *et al*., 2005), *Eucalyptus* in Australia and Brazil (Keenan *et al*., 1997; Parrotta, 1997; Parrotta, Turner, and Jones, 1997; Kanowski, Caterall, and Wardell-Johnson, 2005), *Eucalyptus* and *Pinus* in South Africa (Geldenhuys, 1997), and teak (*Tectona grandis*) in Thailand (Koonkhunthod, Katsutoshi, and Tanaka, 2007) have all recorded understory establishment of native rainforest species. Most of the species recorded would be considered pioneers of initiation or stem exclusion, similar to the plantation tree species

Figure 16.8 A photograph depicting growth for a native species tree planting across a three-row pine canopy removal treatment. The photograph depicts seedling development at 4 years years after planting. *Source:* Mark S. Ashton.

beneath which the species established. However, studies also report the recruitment of late-successional understory and canopy tree species that are dispersed by animals and that would be considered site generalists (Parrotta, Turner, and Jones, 1997; Tomimura, Singhakumara, and Ashton, 2012). Studies have used this knowledge about the potential understory amenability for vegetation establishment beneath plantations to purposely plant site-restricted, late-successional, shade-tolerant species (Ashton *et al.*, 1997) (Fig. 16.8). These tree species provide both important timber and non-timber forest products that would otherwise be lost. Simple two-aged plantation and hybrid plantation natural regeneration systems can be very useful tools to convert wastelands back to a forest composition and structure that would never establish in open conditions (Ashton *et al.*, 2001, 2014).

Another technique to encourage natural regeneration on open land is to simply plant species that have a known foraging preference to bird and bat seed dispersers. In studies by Holl, Nepstad, and others on pastures in Latin America, show the role that planted single trees can have as structures that facilitate animal seed dispersal of other species that regenerate beneath and nearby, thus catalyzing a new second-growth forest (Holl, 1999; Holl *et al.*, 2000; Jones *et al.*, 2004).

Last, but not least, the most complex mixed-species plantations comprise the tree garden systems of many indigenous peoples around the rainforest regions of Asia: in Sri Lanka the Kandyan Home Gardens (Jacob and Alles, 1987); in Borneo the Tembawang (Marjokorpi and Ruokalainen, 2003); in Java the Javanese tree gardens (Marjokorpi and Ruokalainen, 2003); in Latin America, specifically Mexico, the Yucatan pet kot, (Gomez-Pompa, 1987); and in Africa, the Tanzania chagga home gardens (Fernandes, Oktingati and Maghembe, 1984). Tree gardens are literally planted and tended trees grown in mixtures, but individually tended and yield a mixture of fruits, spices, medicinals, and timber. Many are adjacent to the household and can be partitioned into early successional shrub areas, and later successional more shady tree areas. Other tree gardens are tended stands of trees that were planted on old swiddens. Tree size-class and age-class structures are complex and irregular. No commercial operation would be viable but they are currently common as subsistence and supplementary cropping systems (Fig. 16.9).

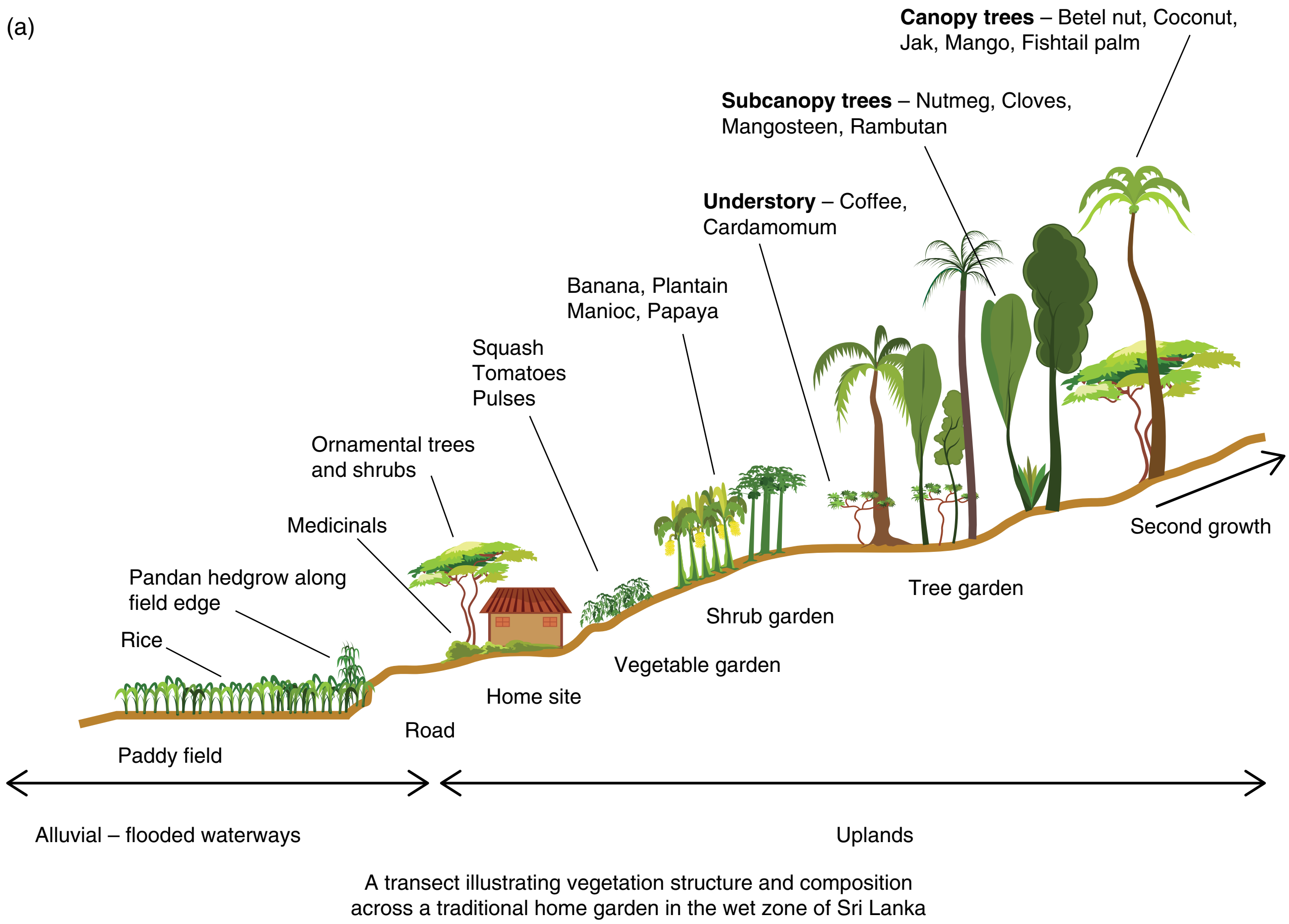
Enrichment Planting and Underplanting in Native Forests

Planting can sometimes be done usefully beneath existing stands or in gaps within them. The purpose of enrichment planting is to supplement the species composition of an existing natural forest. Reasons for enrichment plant are numerous, but some important ones include restoring tree species lost from forests that have been over-logged (Montagnini *et al.*, 1997), and introducing new tree species of additional economic value (Ådjers *et al.*, 1995) (Fig. 16.10a).

In mixed stands, especially in the tropics, **enrichment planting** is sometimes done in lines or gaps that are deliberately opened in the forest in order to establish a few trees of highly desirable species (Ådjers *et al.*, 1995; Montagnini *et al.*, 1997). Such trees *must* be released by frequent cleanings, and it helps if the openings are created with the use of herbicides to kill the roots of the trees that are removed.

The deliberate planting of understories of shade-tolerant species beneath taller trees is called **underplanting** (Fig. 16.10c). It may be done to establish advance regeneration of desirable but absent species, some years before the taller ones are to be harvested (Kenk, 2001). It is also used to introduce understory species to provide such benefits as accelerated nutrient cycling or food and cover for wildlife.

(a)

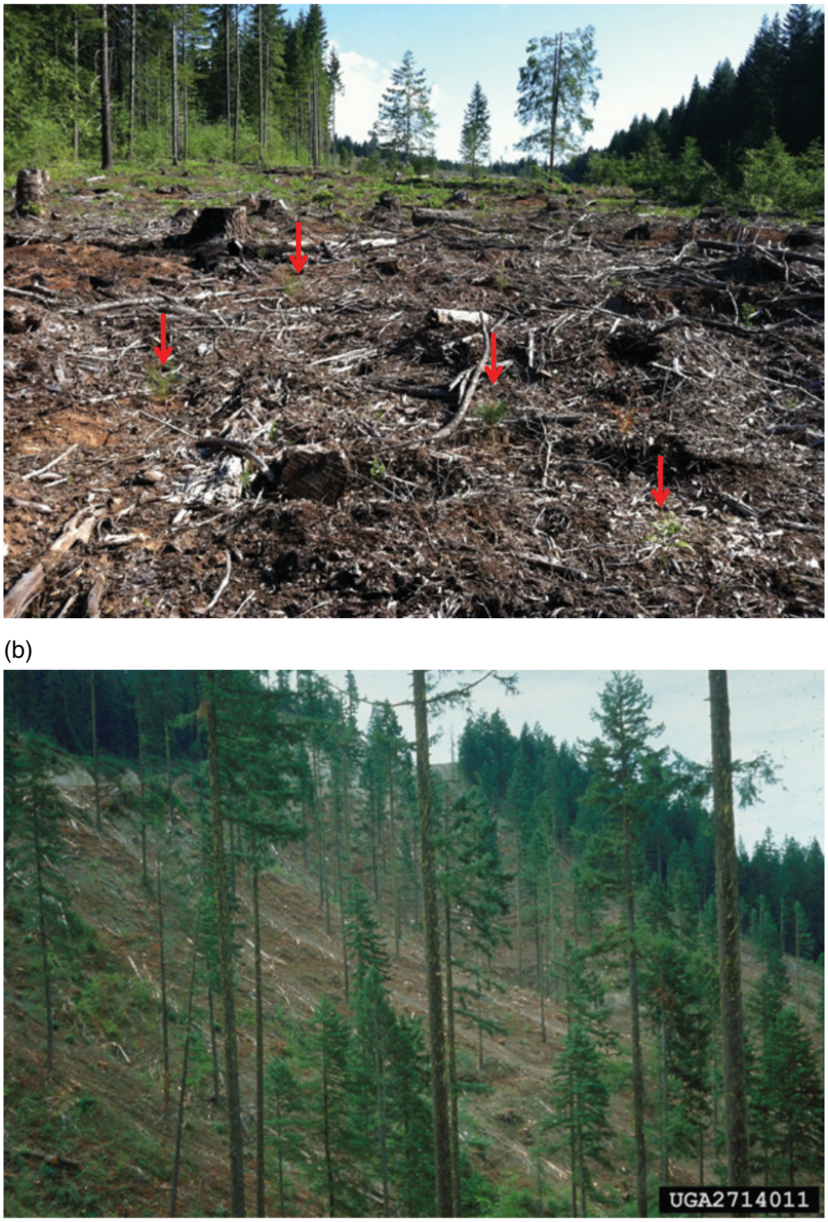


(b)

Figure 16.9 (a) A conceptual diagram of tree garden in southwest Sri Lanka. **(b)** A photograph of a traditional tree garden landscape in southwest Sri Lanka. *Source:* **(a, b)** Mark S. Ashton.

Figure 16.10 **(a)** The use of enrichment line-planting in a cutover hill mixed dipterocarp forest in Malaysia. **(b)** Underplanting of beech in tree shelters to supplement the existing stand. **(c)** Enrichment planting beech in openings to eventually convert a spruce forest to beech in Germany, a land-transformation process common throughout central Europe. *Source:* **(a–c)** Mark S. Ashton.

(a)



(b)

Figure 16.11 **(a)** A single-species planting of ponderosa pine on the east side of the Cascades of the southern Washington. Reserves have been left of the original stand in two ways – as single trees as seen in the background and as a large group (left). This has been referred to as "green-tree retention" in the Pacific Northwest. The red arrows point to planted ponderosa pine in the foreground. *Source:* Mark S. Ashton. **(b)** A variable retention harvest on State Forest managed by the Washington Department of Natural Resources. Single trees of Douglas-fir have been left for structure beneath which Douglas-fir has been planted within volunteer western hemlock, creating what will become a two-aged stand of both planted and natural regeneration origin. *Source*: Douglas Maguire, Oregon State University, Bugwood.Org. Reproduced with permission from Bugwood.org.

On private and industrial lands of the western and boreal regions of the US, Canada, and Scandinavia, residual trees from the prior stand are routinely left either in groups or as scattered individuals within plantations. The term used for this combination is "green-tree" retention (Rosenvald and Lohmus, 2008). In the western US it is a common practice with Douglas-fir and ponderosa pine plantations (Halpern *et al*., 2005), but in the boreal plantations, the species are Scots pine, white spruce, jack pine, and Norway spruce (Vanha-Majamaa and Jalonen, 2001; Montgomery *et al*., 2013). Residual trees are left primarily to add habitat structure to a stand that ordinarily would develop into a single-species, even-aged stand (Fig. 16.11). Residual species that are commonly left are often hardwood species (cottonwood, oaks) or large conifers because of their wildlife value either as a source of mast or as thermal cover.

Low Forest Plantations

Low forest plantations can usually be defined as those plantings of seedling or vegetative origin (e.g., cuttings) that give rise to short-statured multi-sprouting plantations managed over short rotations. After planting, these systems can be dependent on coppice natural regeneration for continued regrowth for a period of time before being replaced with new plantings. There are two categories: (1) single-aged, single-species that are seedling- or cutting-origin plantations that are fast-growing, shade-intolerant species amenable to sprout growth and planted at close spacing for fiber production or land stabilization; and (2) single-aged, mixed-species plantations that are seedlings or cuttings with standards or vegetative pollards planted at wider spacings.

Single-Aged, Single-Species Plantations

Plantation species selected for low forest cultivation are sun-loving, fast-growing early-successional species belonging to pioneers of initiation or stem exclusion. Most are selected from the same group of trees that include the fast-growing, single-species timber plantations, but they have the additional capacity to coppice vigorously. This basically removes the conifers, except species like redwood, and leaves the cottonwoods, aspens, acacias, and eucalypts. These species are grown in intensive densely planted systems to achieve one thing: maximum biomass over a short period of time for fiber production and biofuels. However, there is a caveat to this, in that there are other low forest single-species systems that are focused on leaf or berry production from sun-loving cultivars of understory trees such as tea and coffee. These two cropping systems are treated differently in this text.

Biomass for Fiber, Firewood, and Biofuels

The Salicaceae (willows and poplars) is an important tree family planted for biomass across a wide region of the globe. The fiber is ideal for pulp, and when grown only to a small dimension, the resulting "whips" are used for thatch and weaving. The tree family does not produce dense wood of high BTUs making it unsuitable as firewood or as a biofuel. In a study by Berkvist and Ledin (1998), different planting densities of *Salix* revealed that stand closure was fastest with single-row systems with 3 ft (1 m) between the rows. Biomass yield during the first cutting cycle was positively correlated with planting densities up to, but not higher than, 8000/acre (20,000/ha), suggesting that plantation design can be adjusted without losing yields to meet the requirements of harvesting machinery.

In the southern US, species of choice have been sycamore, sweetgum, and cottonwood for short-rotation pulpwood and biomass. Studies by Davis and Trettin (2006) on sycamore and sweetgum plantations established on low-lying old agricultural lands on the South Carolina coast showed that sycamore grew best and showed no improved growth with drainage as compared to sweetgum. In another study by Scott *et al.* (2004), the addition of nitrogen fertilizer to sweetgum planted on old fields increased foliar demands. Spacing is usually 3 ft (1 m) between trees and 6 ft (2 m) between rows. Rotations are as short as 2 years but can be up to 10 years. Elsewhere, bioenergy plantations are managed in a similar manner but with different species.

To produce biofuel, the tree species of choice has been *Jatropha curcas* (Achten *et al.*, 2008), a fast-growing shade-intolerant tree that can tolerate seasonal droughts and subtropical temperatures, and produces high amounts of oil from its seed. The tree can be direct seeded, planted as seedlings, or planted as cuttings. Spacing is usually at 6 × 6 ft (2 × 2 m) but with increasing spacing, seed yield per tree increases significantly, while the seed yield per hectare (acre) decreases (Achten *et al.*, 2008).

Tropical and temperate tree species that produce high-BTU firewood would be the last group of trees that fit this category (NAS, 1980). Many of these species are legumes. All have an ability to coppice and re-sprout vigorously and are sun loving (see list of firewood species commonly planted in Table 16.7)

Plantings for Stabilization of Eroded Lands

The most common use of low forest, single-species planting for service values relates to water. Where flooding and tidal storms have exposed river banks to erosion and estuaries to excessive siltation, planted vegetation is usually a cheap and efficient solution to stabilizing the soils, and preventing further loss. River and stream banks with severe erosion are often planted with water-loving trees and shrubs like willows, alders, and cottonwoods. Cuttings are easy to collect, even from nearby trees, and can be placed in the ground at 1.3 × 1.3 ft (50 × 50 cm) intervals. Some species that have been used in stabilization efforts were a poor choice for river stabilization because of abilities to naturalize. An example is the use of the invasive tree *Tamarisk* spp. of central Asia in the interior western US (Harms and Heibert, 2006).

Biomass for Leaves and Fruit Crops

Trees and shrubs that have been cultivated as low forest plantations for leaves and fruits were all originally understory plants that have been adapted through breeding

Table 16.7 Tropical and temperate tree species planted for their firewood values.

Tropical plantation species	Family	Region of influence
	Legumes	
Acacia nilotica (babul)		Africa (dry)
Acacia senegal (gum arabic)		Africa (dry)
Albizia lebbek (lebbek)		South America/Caribbean (dry)
Calliandra callothyrsus (calliandra)		Pantropical (wet and dry)
Gliricidia sepium (gliricidia)		Pantropical (wet and dry)
Leucaena leucephala (leucaena)		Pantropical (wet and dry)
Sesbania bispinosa (spiny sesban)		Pantropical (wet and dry)
Sesbania sesban (sesban)		Asia (dry)
Prosopis spp. (mesquites)		Pantropical (dry)
	Non-legumes	
Azadirachta indica (neem)	Meliaceae	South Asia and Africa (dry)
Casuarina equisetifolia (casuarina)		
Corymbia citriodora (lemon gum)	Myrtaceae	Pantropical (dry)
Eucalyptus camaldulensis (river red gum)	Myrtaceae	Pantropical (dry)
Gmelina arborea (gmelina)	Verbenaceae	Pantropical (wet and dry)
Syzygium cumini (jambul)	Myrtaceae	Asia (wet and dry)
Terminalia catappa (Indian almond)	Combretaceae	Pantropical (wet and dry)
Montane tropical plantation species	**Family**	**Region of influence**
	Legumes	
Inga vera (inga)		South America (Andes)
	Non-legumes	
Alnus acuminata (alder)	Betulaceae	South/Central America
Alnus nepalensis	Betulaceae	Himalaya
Alnus rubra (red alder)	Betulaceae	Pacific NW North America
Eucalyptus globulus	Myrtaceae	Pantropical montane
Grevillea robusta (silktree)	Proteaceae	Pantropical montane
Temperate plantation species	**Family**	**Region of influence**
	Legumes	
Gleditsia triacanthos (honey locust)		North America
Robinia pseudoacacia (black locust)		Pantemperate
	Non-legumes	
Maclura pomifera (osage orange)	Moraceae	North America
Melia azedarach (Chinaberry)	Meliaceae	
Morus spp. (mulberry)	Moraceae	Eurasia
Quercus spp, (oaks)	Fagaceae	pantemperate
Ostrya virginiana (ironwood)	Betulaceae	North America

Source: Mark S. Ashton.

programs to select cultivars that grow well in open conditions but retained their propensity to sprout. Tea and coffee are the obvious examples of short-rotation single-species plantations. The planting stock is usually vegetative and clonal, all from one cultivar to ensure consistency and uniformity of the product harvested. The plantings for tea are usually equilateral with 3 ft (1 m) between clonal cuttings of specific cultivars. After several years of weekly leaf pruning, the shrubs are cut back to the base and allowed to re-sprout. This happens at intervals of 6–18 months until the plantation is replaced, often after 30 years of harvesting (Colton and Murtagh, 1999). Coffee plants are of seedling or clonal origin that are planted in rows approximately 3 ft (1 m) apart, with plants spaced 1.5 ft (50 cm) apart with each row. The fruits are born behind the leaves of each stem. The plants are pruned back to the base approximately once every 3 years to re-invigorate the growth of the plant (Smith *et al*., 1992).

Single-Aged, Mixed-Species Plantations

This is an unusual category to have in low forest plantation systems. Tree crops that are on short rotations of low stature, and that require open conditions for high productivity, do not need partial shade or other species that grow in intimate mixture. The only product category of those listed above that could have associated taller trees incorporated into a low forest system that would be analogous to a true coppice system in natural regeneration methods would be those crops including leaves or fruits. These are the understory trees and shrubs that have been bred to become sun adapted. The original shade varieties of these crops required shade trees that facilitated their growth. In addition, particularly for smallholders as compared to large industrial operations, shade varieties could tolerate other trees planted for timber or food as a mixed cropping system. Shade trees (analogous to standards in coppice systems) are commonly planted in low forest plantations for crops such as tea and coffee, include nurse trees that also fix nitrogen (*Gliricidia sepium*, *Erythrina* spp.), trees that produce timbers (*Cordia alliodora*, *Cedrella odorata*) (Fig. 16.12), and trees that produce fruits and spices (*Durio zebithinus*, *Syzygium aromaticum*) (Beer, 1987).

Protection of New Plantations

Plantations are as subject to damage from biotic and atmospheric agencies as natural stands in the same stage of development, and often even more so. Losses in artificially regenerated stands represent greater wastage of direct investment than comparable damage in stands that have been reproduced naturally. The large investment in plantations requires a correspondingly heavy outlay for protection that should be regarded as part of the cost of artificial regeneration. Disease and genetic resistance of trees produced in breeding programs have been one success story with, for example, the resistance of certain loblolly and slash pine genotypes to fusiform rusts.

Wild animals are a significant cause of damage to plantations. Often, it seems that they find fertilized nursery-grown seedlings more palatable than natural seedlings of the same species. Although there are no certain measures of control, it is generally best to attack the problem by indirect means. Rodents tend to prefer dense cover and can sometimes be discouraged by eliminating low vegetation before planting.

Progress in the development of effective repellents for use against larger animals has been slow, but some compounds now on the market are occasionally satisfactory. Another solution is to avoid planting in places or during years with high populations of the most damaging animals. Sometimes valuable planted trees can be protected by enclosing planted areas with fences, or planted trees can be protected with tall tubular tree shelters (Kittredge *et al*., 1992). Overpopulations of deer and other large herbivores are generally controllable only by deliberate hunting programs.

Damage by domestic grazing animals may be controlled by proper herding or fencing, depending on the custom of the locality. Sometimes livestock can be lured away from planted areas by putting out salt elsewhere.

One of the most important causes of plantation failure is competition with other vegetation. All too often, plantations are established and then left to fend for themselves. Even those made in open areas can be overwhelmed by fast-growing vegetation. The costs of releasing plantations can be reduced by avoiding the temptation to plant up brushy areas or spots adjacent to existing trees. The underplanting of trees beneath brush or existing stands of trees usually involves a definite commitment to carry out subsequent release cuttings.

The gaps that develop in new plantations from scattered losses of planted trees can sometimes be corrected by subsequent planting or refilling. If this is not done soon (and sometimes even if it is), the trees of the second planting get overgrown by the initial survivors. Because most losses occur during the first year, the ideal time for refilling comes a year after the first planting. Even then it is good to plant stock that is at least as tall as the

(a)

(b)

Figure 16.12 **(a)** A low forest planting of hill-country (high elevation) coppiced tea bushes in the highlands of south India with pollarded *Grevillea robusta* trees spaced at distant intervals to provide a light shade. *Source*: Woodbriar Group. Reproduced with permission from Woodbriar Group. **(b)** A low-country (low elevation) tea plantation in coastal southwest Sri Lanka with a dense canopy of shade coconut trees to counteract the hotter conditions of the sun. *Source:* F.-X. Delmas. Reproduced with permission from F.-X. Delmas.

established competitors or is of some intolerant species that will grow faster than the original species.

Refilling is most effective in replacing large patches of dead trees, provided that the causes of the initial failure are identified and either corrected or evaded. If only scattered trees have survived, it is often best to eliminate them and start a whole new plantation. In the common situation in which the losses are well scattered, refilling usually proves to be a costly waste of effort.

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Part 4

Post-Establishment (Intermediate) Treatments

Understanding the concept of growing space and self-thinning and their application to various stages of stand condition for improved product yields and services desired by people.

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

17

Tree and Stand Growth

Introduction

The first part of this chapter introduces the patterns of growth of individual trees. It includes primary growth (extension of shoots, leaves, and fine roots) and secondary growth (thickening of stems, branches, and roots). An explanation is provided for how trees prioritize growth allocation of carbohydrates (sugars) from the process of photosynthesis. The important aspect of "growing space" is presented, as well as how crown and stem morphology can differ among tree species. The nature of stem form and wood properties are also explained.

The second part focuses on stand-level patterns of growth and productivity in relation to climate, site, and stand development age. The methods are described for measuring productivity over time for both stands and individual trees.

The third part of this chapter is concerned with the complicating effects of thinning on stand productivity, primarily dealing with the growth and yield response.

Growth within Individual Trees

Carbohydrate Allocation in Trees

Trees, like all green plants, capture solar energy through photosynthesis (Salisbury and Ross, 1992; Larcher, 2001). This energy is briefly stored in the electrons of chlorophyll molecules and is then used to synthesize sugar (glucose) from carbon dioxide and water in the interior of the leaf. In the next step, simple carbohydrates are formed from sugar and are translocated throughout the tree. Some of these carbohydrates are used for respiration to meet the basic metabolic needs of the living cells and to catalyze the growth of new cells. Others are used as the building blocks for larger and more complex carbohydrate molecules, principally cellulose, hemicellulose, and lignin, which form the structure of cells and collectively make up most of the mass of a tree. Much smaller amounts of proteins and lipids are also formed. The amount of carbohydrate produced by a tree depends mainly on the size of the crown (the total mass of foliage) and the ability of the roots to supply the foliage with water and nutrients (Larcher, 2001).

There are two basic types of growth in most trees. **Primary growth** consists of the extension of shoots and leaves aboveground and of fine roots belowground. Plants have stem cells (similar to those in animals), which are not genetically determined, so they can form a variety of cell types. In plants, stem cells are called meristems or meristem cells. New shoots and roots develop from apical meristem cells in the buds and root tips; they divide and differentiate into the many cell types that form leaves, stems, and roots. (The terms 'apex' and 'apical' refer to the tip of a plant shoot.) **Secondary growth** involves the increase in the thickness of woody stems, branches, and roots. This growth is initiated by cambium meristem cells that form a layer encircling the stem and branches of the tree; these meristem cells divide and differentiate into xylem and phloem cells. Just outside the phloem, there are bark cambium meristem cells that form new layers of bark. The growth rates of all of these tree structures (both primary and secondary) depend on the overall amount of carbohydrate produced by the photosynthesis of the tree.

As a tree's vigor increases or decreases over time, the rates of growth and other functions of the tree do not increase or decrease proportionally. A hierarchy in carbohydrate allocation exists among the parts and functions of the tree, and it is under strong genetic control (Fig. 17.1). The highest priority is to sustain the function of living cells by rebuilding protein molecules and repairing cell membranes. The use of energy for this purpose is called **maintenance respiration**. Most of this activity occurs in the foliage, to maintain the photosynthetic structures and chemical reactions. The next priority is primary growth, which produces the foliage and fine roots that are vital to the survival of the tree. An important aspect of allocation to primary growth is that it includes the height growth of the tree (that is, the extension of the shoot at the apex of the tree). Reproduction (growth of flowers, strobili, cones, fruits, and seeds) also

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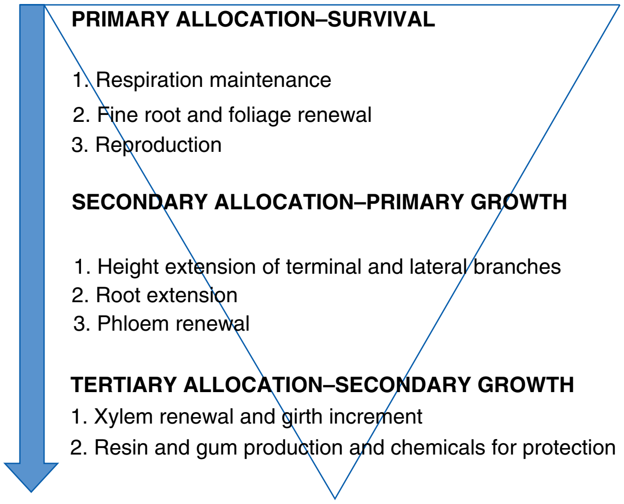


Figure 17.1 Priority allocation of carbohydrate in a tree. *Source:* Mark S. Ashton.

has high priority and competes with shoot and root extension growth for carbohydrates. However, in some species, large seed crops are produced only periodically (**masting events**), with little or no allocation to reproduction in other years. Growth in diameter increment has been shown to be higher during non-mast years as compared to mast years.

The next priority is the storage of carbohydrates in stems, roots, and branches (and in the older foliage of evergreen species, as well). This storage plays a critical role in future allocation and growth because the sugars are stored in a stable condition as starch, but then can be mobilized back into sugars when needed. Secondary growth of the woody parts of the tree has relatively low priority. The functions that wood growth provide are: (1) to produce new layers of cells for transporting water and nutrients in the xylem, and sugars and other compounds in the phloem; (2) to provide for physical support of the tree by thickening the stem and roots. These functions are clearly important for the survival of the tree, but are provided by multiple years of functioning xylem and phloem. The dead xylem in stems, branches, and roots also gives additional structural support. The lowest priority in allocation is the production of defensive chemicals, such as resins in the wood of many conifer species, and tannins in the leaves of oaks and other species (Salisbury and Ross, 1992; Barbaroux, Breda, and Dufrene, 2003).

One carbohydrate allocation, **growth respiration**, relates to nearly all of the functions described, as it occurs anywhere that plant tissues are being constructed. This respiration occurs proportionally to the rate of growth of foliage, root tips, wood, bark, flowers, or seeds in any location in the tree. It cannot be placed in a specific priority level within the hierarchy. It should be noted that there is no difference in biochemical process between growth respiration and maintenance respiration. Both of these terms are used so as to differentiate allocation of respiration energy between the two functions: growth and maintenance.

The Effect of Carbohydrate Allocation on Tree Growth

The priority rankings of different functions of the tree will show an overall pattern (as described in the previous section), but this description may make it appear that the tree is being controlled by a computer program. It is useful to see how these allocations really work over a growing season. They are controlled by a source–sink relationship of sugars that functions principally in the phloem and are mediated by plant hormones (auxins, cytokinins, gibberellins, abscisic acid). For example, when leaves are fully active and producing sugars from photosynthesis, they would be a source of sugars. Fine roots growing at this time would be using sugars to build cellulose and other molecules to construct new cells; thus, the roots would be considered a sink because the sugars are disappearing as they are combined to create cellulose and other structural molecules to build cells. The sugars would be flowing from high sugar concentrations in the leaves to low sugar concentrations in the root tips. Plant hormones control the activity of cell divisions within the various parts of the tree to turn them from sinks to sources and back to sinks (Salisbury and Ross, 1992; Larcher, 2001).

A deciduous tree in a temperate-zone climate exemplifies these changing activities during its growing season. In the spring, auxins initiate the growth of buds in the tree crown to produce shoots and leaves, and they begin to expand acting as strong sinks. The sugars are being mobilized from stored starch in large roots and the stem which are now acting as strong sources of sugars. Then, as leaves open and expand to full size, the source–sink patterns reverse. The leaves now become a source of sugar from photosynthesis, and the storage cells in the roots and stems act as a sink, converting sugar to starch and rebuilding the reserves for next year. Next, the cambium meristem is activated by auxins all along the branches and stem. Sugars are translocated down the phloem from the foliage to the sink in the wood cells. There, sugars are incorporated into the cellulose of new xylem and phloem cells, as well as made into defensive chemicals within the wood.

These patterns of growth are important for understanding how a tree grows. Consider a loblolly pine tree that is growing in a young, dense, loblolly pine stand, where the canopy has not closed yet. The tree's large crown would be able to supply sugars for all parts and functions of the tree. As the canopy begins to close,

bottom branches become shaded, and the total foliage would be reduced, so photosynthesis would decline. The weakest sink would be resin production, so this makes it more likely that the southern pine beetle would be able to bore through the bark into the phloem, stealing the sugars. If the tree had more sugars, then large amounts of pitch would block or kill the beetles. Stem diameter growth will then decline, especially in the lower part of the stem, which is last in line for the sugars that are allocated for the stem. However, the tree had continued to grow in height at the same rate as in past years. It had already obtained all the sugars that were needed from that which was stored from last year. However, if crown competition within the stand limits the crown size even further, the tree would not be able to store an adequate amount of sugars as starch for the following year. So, during the next growth season, the leader would not grow as much in height as in previous years. The crown size of this tree must be reduced to a very small size in order to not be able to provide the stored sugars for the growth of shoots and leaves in the crown; trees of this sort are not long for the earth, unless more growing space is given for the crown to expand. Of course, not all the pines will follow this trend. Pines that have taken the growing space away from those like this one, are going to remain strong and healthy. Only the strong survive. This means that those trees that start to lose the battle to secure crown growing space and resources will usually die. Those trees of the same species that obtain more growing space will win over their same-species competitors.

Tree Structure and Development

A great diversity exists among tree species in the structure (or architecture) of the stem and main branches. A division into two basic types can be made, to recognize an important structural difference. Some species have an **excurrent form**, with a main vertical stem that extends to the very top of the tree, and with branches that are distinctly smaller in diameter, growing in a roughly horizontal orientation. Other species have a **decurrent form**, with branches that begin roughly horizontal but then curve upward to become vertical (see Oliver and Larson, 1996). The main branches on trees of decurrent species grow so large in size that they may nearly equal the diameter of the original main stem; in many cases, a main stem cannot be identified in the upper part of a mature tree (Fig. 17.2).

Nearly all canopy tree species exhibit excurrent form when they are saplings and poles, ascending toward the canopy. Most gymnosperms, such as pines, spruces, Douglas-fir, and gingko, maintain that form as they develop into large mature trees. Most angiosperms, such as oaks, maples, birches, and mahogany, lose the excurrent form as they grow beyond the sapling and pole stage.

(a)

(b)

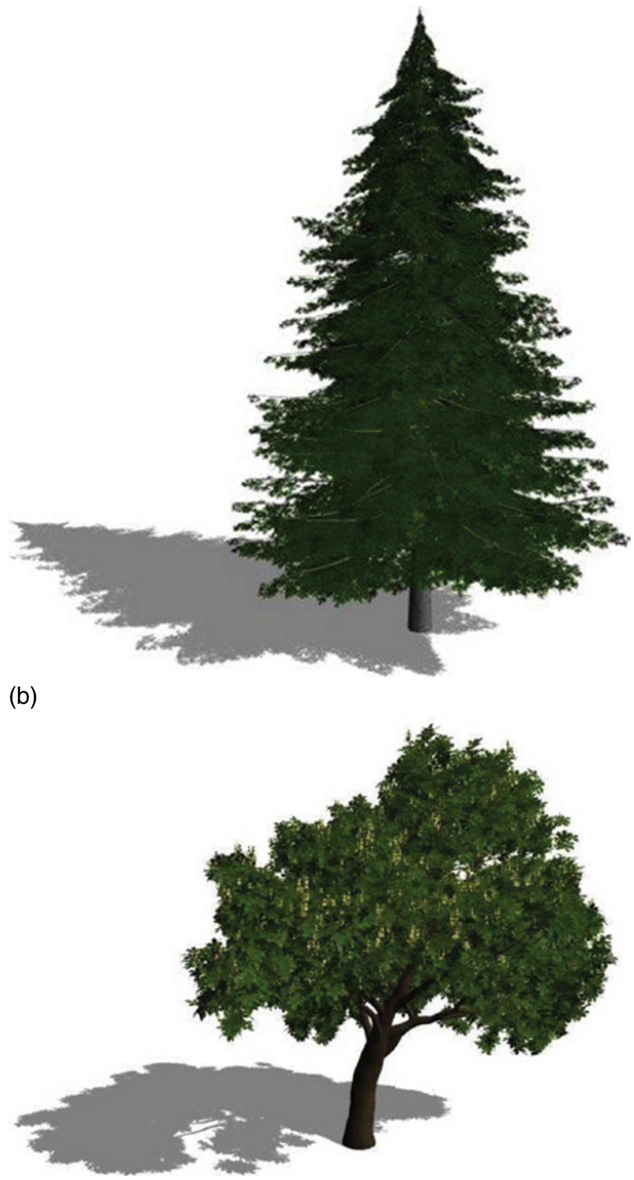


Figure 17.2 The silhouette of a tree with (a) an excurrent form (Norway spruce); and (b) a decurrent form (horse chestnut). *Source:* (a, b) F. Cooper, Little Stick. Reproduced with permission from F. Cooper.

Factors that shift angiosperm species from excurrent to decurrent form appear to be related to: (1) repeated damage to the crowns, (2) timing of canopy exposure and full sunlight, or (3) initiation of crown flowering and fruiting. However, the division among structural types between the two main groups of trees is not complete. Some angiosperms such as yellow-poplar and sweetgum maintain the excurrent form to a very large size, unless the stem is damaged.

Stems and branches in both structural types are inherently negatively geotropic (which means that they grow away from the earth in an upward direction).

In excurrent species, the shoot at the apex of the tree exerts strong **apical control** over branch growth. When a new shoot begins to develop from a bud on the main stem, it begins to grow vertically, but is quickly controlled by hormones translocated from the leader (the top shoot of a tree is often called the **leader**). This causes the branch to grow in the direction of the original orientation of the bud, usually somewhat above horizontal. Secondary growth of the branch is also controlled, and the new layer of wood is added to the branch at very low rates, even if it is a fast-growing, vigorous branch, and so the branch stays much smaller in diameter than the main tree stem. The influence of the leader at the apex of the tree is called **apical control**, which is a result of plant hormones that are produced in the leader and translocated to other parts of the tree. This control of branch growth is sometimes referred to as "epinastic control," although the term "epinastic" refers only to control of the angle of the branch, not the branch diameter growth rate. "Apical control" is the more commonly used term for the overall pattern.

If the leader of an excurrent species is cut off, some of the young branches just below the leader will be released from apical control, and one or more will curve upward and grow vertically. This occurs with any excurrent species when the leader is cut or broken. However, older branches that are lower in the tree are not affected by the loss of the leader; they maintain their horizontal or slightly upward orientation. In decurrent species, apical control appears to have much less effect on branches. Branches of these species also begin growth that is oriented with the initial bud angle when they are young, but then they routinely grow upward, with the branch tips eventually being almost equal to the height of the main stem tip, and nearly equal in diameter, as well.

The Concept of Growing Space

If a tree has growing space open in all directions, the branch growth of that tree will form a circular, symmetric crown. However, if growing space is limited on some sides of the tree by the crowns of other trees or other barriers, the crown will become asymmetric. Branches on the well-lit sides will produce a greater number of buds, and the shoots developing from those buds will have greater growth rates, compared to shaded branches. Thus, branches function somewhat autonomously from one another. Carbohydrates produced by the photosynthesis of foliage of each branch are not shared evenly among branches to maintain a symmetric crown. Vigorous branches export carbohydrates to support the current growth of stems and roots and to provide storage for future growth, but this export does not include other branches. When the stored carbohydrates are mobilized at the beginning of the growing season, more will be translocated to the vigorous branches with more buds, which act as strong sinks for carbohydrates. Differing auxin concentrations in the various parts of the crown are the major mechanism for guiding the amount of sugar to the sites for growth. An old branch at the bottom of the crown, shaded by the branches above, will receive only a small portion of the stored carbohydrates because it has few buds. When photosynthesis produced by the branch can no longer meet its growth and respiration requirements, it will die. The same will happen with young branches high in the crown, if they are shaded by taller adjacent trees.

The development of asymmetric crowns improves the growth and survival of a tree by allowing it to efficiently capture free growing space. This can be observed at an edge between a forest stand and a field (Fig. 17.3). With most hardwood species (decurrent form), the edge trees will develop a longer crown on the field side with longer branches that have larger diameters, compared to the forest side. This highly asymmetric crown may become so unbalanced in weight that the tree will lean away into the open growing space. In these situations, it appears that the trees are phototropic (i.e., with the leader growing toward higher light intensity), but this is not the case. Phototropism has little effect on branch or stem orientation of trees past the seedling stage. As the heavier side of the crown begins to pull the tree over, the leader continually grows vertically. The growth of reaction wood in the stem (described later in this chapter) helps to bend the tree back to vertical, thus producing a curved tree. This happens with edge trees along streams or with trees growing in a stand with canopy gaps. With conifer species (excurrent form), a similar effect happens, but the most noticeable effect is the longer crown on the field side rather than a curvature in the stem. Because of the stronger apical control in conifer species, the branches on the field side do not increase in length or diameter to the same degree, so the effect will be only moderately larger diameter or longer branches. Generally, there is not enough differential weighting of the crown to cause the tree to lean.

The structural form of the root system is generally hidden from view, and so it is not as well understood as that of the aboveground portion of the tree. However, the main functions are quite clear: the fine roots take up water and nutrients, and the large woody roots anchor the tree in the soil, translocate water and nutrients, and store and translocate carbohydrates. In many tree species, the seedling produces a taproot that grows vertically beneath the stem, providing physical stability and uptake of water. Other roots grow horizontally, staying close to the soil surface where water and nutrients occur in high levels. They extend their roots in all directions, similar to that of branches. Fine roots proliferate where the combination of water, nutrients, and oxygen are

Figure 17.3 A photograph of the crown response to growth along a field edge. *Source:* Mark S. Ashton.

available, and they progressively thicken into woody roots. However, where fine roots encounter soils with few resources, they will slow in growth or die. Thus, asymmetric root systems develop and they appear to grow in a hydrotropic orientation (that is, toward greater water and nutrient availability), but this is not so. As with branches, it is a case of symmetric "exploration" of growing space, with differential survival in each direction based on the different amounts of resources in each direction.

Because roots do not have to support their weight, roots can extend much further than branches, beyond the edge of the tree crown. They can grow past the root systems of neighboring trees. When roots of neighboring trees of the same species grow across one another, a root graft can occur. As the roots enlarge through secondary growth, a union can form between the cambium, phloem, and xylem layers, such that water, nutrients, and carbohydrates are translocated from one tree to the other. In some single-species stands (mostly of conifer species), the trees that are clearly individuals aboveground have a single common root system belowground. This can be seen where tree stumps can remain alive for years after the tree has been cut. Dye that is injected into one tree stem will often be detected in a neighboring tree that was not injected with dye. There is some evidence from the tropics that trees can develop functional root grafts among different tree species, but only if the species are closely related. Similarly, there is evidence that carbohydrates may be exchanged between Douglas-fir and paper birch (Simard *et al.*, 1997).

There is another aspect of carbohydrate allocation that was not described earlier in this chapter, which deals with the balance between the aboveground and belowground structure and function of woody plants. When water and nutrients are in limited supply on a forest site (as on a dry sandy soil), the translocation of carbohydrates from the aboveground tree to the root system is increased. This allows greater growth of fine roots, which increases water and nutrient uptake. The opposite occurs when soil resources occur at high levels. On a moist, high-nutrient site, more carbohydrates would be translocated to the shoots. This allocation maintains a physiological balance between fine root and foliage functions. This means that tree biomass is not balanced between aboveground and belowground; it will vary. In areas with high precipitation, the belowground biomass is generally only 20–30% of the total tree biomass. In arid regions, shrubs may have 50–70% or more of the total plant biomass in root systems.

Stem Growth

The stem of the tree is of greatest economic concern for timber production, and is also vital for supporting trees that are destined to grow to old-growth stature. Therefore, it is worthwhile to examine the details of stem growth in greater detail. The growth of woody portions

of a tree is so low in carbohydrate-allocation priority that if anything reduces the amount of photosynthesis, it will likely result in a reduction in stem growth, even though other parts of the tree might not be affected. This is why foresters can control the diameter growth by thinning the stand in order to allow the crown to grow larger. One rough but convenient index of the ability of the crown to supply sufficient carbohydrates for stem growth is the live-crown ratio (LCR), which is the stem length within the living branches divided by the total height of the tree, generally stated as a percentage.

Stem growth is based on current-year carbohydrate produced in the foliage of branches and exported to the stem. The annual ring is added as the outer layer of the stemwood, starting at the top of the tree and progressing downward. First, plant hormones activate the cambium to undergo cell division, and then carbohydrates provide the materials for the structure of the cells. It may take several weeks for the growth activity to progress from top to bottom of the stem of a large tree. The width of the new ring of wood generally increases, as it progresses from the top of the tree to the base of the live crown. For vigorous trees with large LCRs, the layer of wood continues to be added below the crown, but with declining ring-width. To understand this pattern of wood growth, it is helpful to think of the ring area rather than just the ring-width. The ring area added may remain constant along the stem, but the ring-width becomes thinner because it is being spread around an ever-increasing circumference of the stem as the wave of growth moves down the tree.

With vigorous trees in or above the main canopy, the mechanical stress caused by wind blowing on large crowns creates a hormone-mediated response that translocates more carbohydrates and creates additional diameter growth at the stem base (called **butt-swell**). On the other hand, low-vigor trees with low LCR (tree A in Fig. 17.4) have fewer carbohydrates available for wood production. A progressively thicker ring of wood is laid down along the stem within the live-crown portion of the tree, but then the ring width declines rapidly in the lower part of the stem. This is not just the result of an increasing circumference of the lower stem; the ring area of wood is reduced in absolute terms. In fact, trees with very low vigor may not have enough carbohydrates to add any new wood at the base of the tree. These trees will not complete an annual ring along the lower stem. Trees with such small crowns are generally in the lower canopy or in a very dense main canopy, and are not subject to mechanical bending from wind, so there is no response that provides additional diameter growth to produce a butt-swell either. Thus, the two factors that control the shape of the growth layer on a tree stem are (1) the total size and length of the crown, and (2) the degree of bending stress from wind.

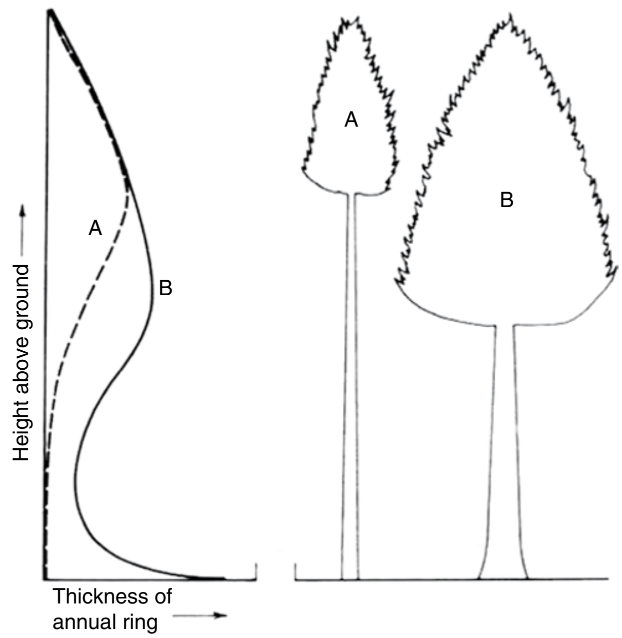


Figure 17.4 The variation in the thickness in the sheath of wood annually laid down on the central stem for a small-crowned tree (A) that is barely surviving, and a vigorous tree with well-developed crown and butt-swell (B). Note that there are peaks in ring thickness near the base of the crown of each tree. *Source:* Yale School of Forestry and Environmental Studies.

Effects of Stand Density and Thinning on Stem and Wood Characteristics

Stand density (the number and sizes of trees in a stand) is directly related to the degree of competition among individual trees. This competition affects tree vigor, apparent in the LCR, which in turn affects stem form and wood characteristics. These effects can be shown by comparing diagrams of three trees of the same conifer species and of the same age (Box 17.1) that have grown in stands with different histories of stand density.

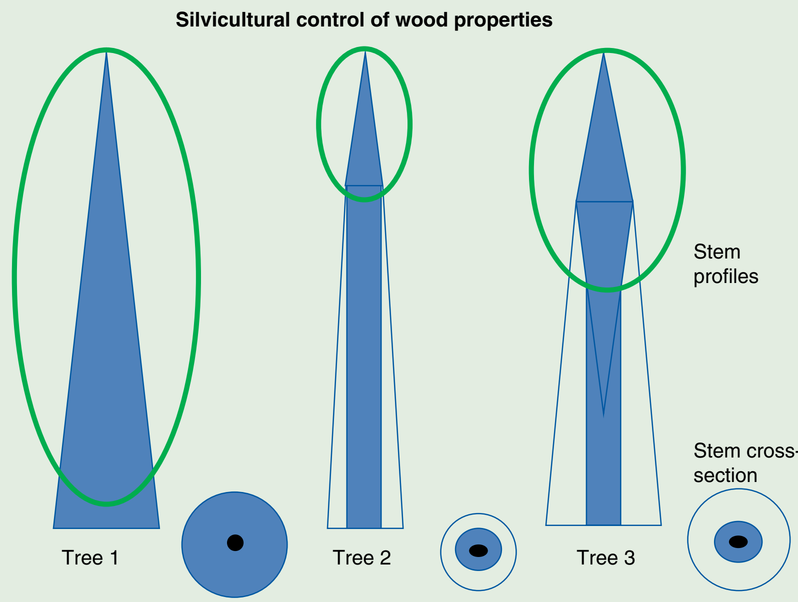
Stem Form

An open-grown tree clearly has a larger diameter at breast height (DBH) than the tree in a dense stand, but the differences in taper must be taken into account to determine accurate stem volumes. The measure of DBH is within the zone of butt-swell, and that can give exaggerated impressions of the growth of stem volume. It is unfortunate that trees are tall and people are short because it would be more reliable to take the basic measure of stem diameter at some point higher than 4.5 ft (1.4 m). In any case, methods exist to assess the degree of taper, which include both butt-swell and upper-stem taper. In the United States, the Girard form-class method is frequently used to determine taper by measuring the stem diameter at the height of 4.5 ft (outside bark) (1.4 m) and at the height of 17.5 feet (inside bark) (5.3 m), which is expressed as a percentage of the upper diameter

Box 17.1 Comparing stem growth and wood formation of trees with histories of different stand density.

Tree 1 has grown in a stand with such low density that the tree is open-grown (Fig. 1). Tree 1 has a live crown ratio (LCR) of 100%, meaning that the live crown extends to the ground. Tree 2 has grown in a much denser stand, and has an LCR of 20%. Tree 3 had initially grown in a stand with a density similar to that of Tree 2, until a thinning treatment substantially reduced the density, and Tree 3 then grew in the more open stand; its LCR is 50%.

In all three trees, stem diameter increases from the top to the bottom of the stem because the stem is progressively older (with more annual rings) from top to bottom. This is seen most readily in the open-grown tree (Tree 1), in which stem growth produces an annual ring that is nearly constant in width along the entire length of the stem (meaning that wood volume growth increases steadily along the stem). This growth pattern produces a high degree of taper, and the stem form approximates the shape of a cone. This is because the crown is of sufficient size to allocate surplus carbohydrate to the weakest sink, the growth increment in girth. The stem of the tree growing in a dense stand (Tree 2) has increasing ring width within the crown, but declining ring width below the bottom of the crown. This will produce a stem with a conical shape within the live crown, and a more cylindrical shape (i.e., with less taper) in the lower stem. This is because little surplus carbohydrate makes it from the live crown to parts of the stem lower down (see Fig. 17.4). Tree 3 is intermediate with a renewal of growth increment down the stem because of crown expansion and increased carbohydrate production that can be re-allocated back down the bole.



Box 17.1 Figure 1 Stem and live crown profiles of an open-grown tree (1), a tree grown under high competition in a dense unthinned stand (2) and a tree grown in a dense stand that has subsequently been thinned (3). Blue indicates crown (juvenile) wood and white indicates mature wood. The same colors in the stem cross-section profiles represent mature and crown wood. Black circles represent the pith. *Source:* Mark S. Ashton.

divided by the lower diameter. Thus, both taper and bark thickness are included in the measure, which is used to modify the standard tree volume equations (Table 17.1).

When trees are grown rapidly with substantial taper, the shortcomings become obvious at the sawmill. A common method of sawing is to make cuts that are parallel to the axis (the pith) of the stem. The first cuts remove the **slab wood** (the outer planks with the butt-swell) to create a **cant** (essentially a square log). A good deal of the extra growth in a highly tapered tree will be lost in the slab wood. Furthermore, the annual rings (called the **grain** in the terminology of wood technology) are aligned with the taper of the stem, which is at an angle to the axis of the stem. Thus, the sawn boards have the grain at an angle to the board, a characteristic called **diagonal grain** or **cross grain**. These boards are prone to warping. Stems that are more cylindrical have grain that is more closely aligned to the stem axis, and therefore to the sawn boards, so the problem of warping is reduced (Box 17.2).

Another consequence of the differences in stem taper in trees has to do with the risk of wind-throw. The high carbohydrate-allocation priority of stem height growth means that trees in stands of different densities (such as Trees 1 and 2 in Box 17.1) both have similar heights but substantially different diameters. This can cause a structural imbalance for trees in dense stands because the thin lower stem has little strength to overcome the wind stresses, even though the sail area of the crown is also reduced. A simple measure that is used to assess the risk of windthrow is the **height:diameter ratio** (H:D ratio). This ratio is calculated by dividing the total tree height by DBH, making sure that the same units (such as inches or centimeters) are used for both measurements. Tree 2 would have

Table 17.1 Girard form class values for several common North American tree species from the east. Values depict differences among regions and species. Greater values are associated with smaller-statured trees on more nutrient- or drought-stressed sites with lower productivity.

	Northeast	South	Lake states
Eastern white pine	80	–	78
Eastern hemlock	78	–	77
White oak	78	78	78
Red oaks	78	78	78
Yellow-poplar	80	81	80
Beech	84	82	82
Hickories	78	77	78
Cottonwood	78	78	78

Source: Mark S. Ashton.

a higher H:D ratio than Tree 1, and as the ratio becomes 100 or more, the risk of windthrow increases.

Wood Properties

The pattern of tree growth creates a complicated pattern of wood properties within the stem that becomes more noticeable once the log is milled. The differences in wood density, stiffness, warping, and shrinkage are important in the end use in wood products, once they are dried. When the leader of the tree undergoes extension growth, the wood produced in that first-year stem is called the **pith**. Buds grow on that shoot and develop into branches as the stem thickens with layers of wood. The wood produced in the portion of the stem with live branches has different properties. Most research has been done with conifers including eastern white pine (Seymour and Smith, 1987), Douglas-fir (Bailey and Tappeiner, 1998), and loblolly pine (Baldwin *et al*., 2000). Generally, the wood in this area of the tree grows rapidly, producing wide annual rings, and the wood cells that are produced have lower density and are shorter (in the vertical dimension). They also have the propensity to bend or shrink because of the structure of the cell walls (Gartner *et al*., 2002). These properties lower the value of wood for most uses. This wood has several names. The most common is **juvenile wood**, but this term leads to confusion because it seems to indicate that it is the wood grown in juvenile trees. That part is true, but it really means the wood in the juvenile part of a tree, regardless of the tree's age. So not only will juvenile wood exist around the pith of the young tree stem, it also is the wood growing on the part of the stem with live branches. The term **crown wood** is suggested as a better term; **core wood** or **pith-associated wood** have also been suggested as terms for the same thing. The crown wood is gradually encased by a transition to **mature wood** which has thinner growth rings, higher density (in most species), and less probability to shrink or warp (Maguire, Kershaw, and Hann, 1991; Pape, 1991) (see the latter section of Box. 17.1).

One mistaken view that has long persisted is that the strength of wood is directly controlled by the rate of stem growth, and that conifer wood, such as hard pines and Douglas-fir, used for construction, is weakened by fast growth. This is based on the idea that the early wood (with lower density) is increased more with fast growth. However, thinning increases the ring width of course, but also usually increases the proportion of late wood (higher density). This is actually not a problem since the ratio remains the same. The problem is not the faster-growing wood of mature wood. The problem is the crown wood. Grading of lumber sometimes uses ring width but it really is just using this to eliminate the crown wood from construction grades.

Knots

The presence of knots in wood is a serious defect. The center core of any tree stem has branches that originated on the small young stem. The stem grows larger in diameter and continues to bury the old part of the branch while the new part continues to grow to form the branches in the tree crown. When the branch dies because of being shaded from other trees or branches higher in the crown, it will take some time until it begins to rot and then breaks off. After the main tree stem grows in diameter past the end of the dead branch, only then is clearwood being produced. When a large tree is being sawn at a sawmill, many of the outside boards will be clearwood. The next boards will contain black, partly decomposed knots; these were the slices of the dead branches. Farther into the center of the stem, there will be boards with red, non-decayed knots that are from the living branches that had been buried in the stem.

The problem of knots is so great that the silvicultural method of pruning branches was developed to eliminate the problem of knots in the main stem. The problems and methods to deal with knots are described in detail in Chapter 19.

Relationships of Crown Morphology to Stem Among Species

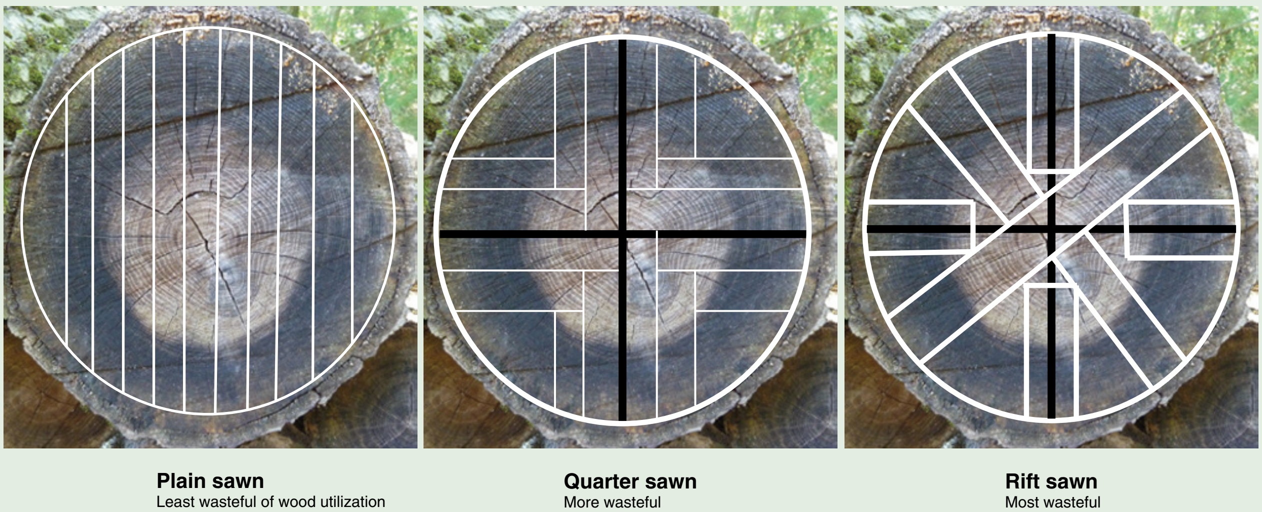
As can be predicted, tree species have different abilities to photosynthesize and allocate carbon for maintenance of living tissues (respiration), reproduction (flowering and fruiting), fine root growth, leaf production, height growth, and stem girth increment. Efficiency in growth allocation to stem increment can be gauged by a ratio of a measure of crown size (leaf area) to stem area. One such measure is the ratio of sapwood to leaf area (Table 17.2) (Tyree and Ewers, 1991). Fast-growing tree species can have a relatively high leaf area per sapwood

Box 17.2 The different kinds of sawn timber from the bole of a tree.

Plain sawing is the most common method of sawing a log (Fig. 1, left). It is also the simplest and involves a parallel series of cuts through the entire log. This is the least wasteful of the wood for producing sawn timber, but because the grain of the wood changes across the board, differences in the drying process can cause differences in tension which can lead to twisting and bowing. Flooring and other high-quality visual products can take on moisture from the air and then warp. Often, dry boards will absorb moisture from the atmosphere and will become distorted. Appearances are also variable because the wood was sawn in one direction only. This means the radial and tangential wood grain can be seen in the same or adjacent board.

Quarter sawing requires cutting the log radially along its length into four quarters (Fig. 1, center). Once quartered, it involves just plain sawing all the way through. This is the common method for producing flooring and other veneers and visual woods (especially oak) because the radial pattern of the growth rings is consistent across boards and warping is not such an issue because there is less variability in tension during the drying process.

Rift sawing is the most wasteful in producing sawtimber but the most visually appealing and the most resilient to warping and distortion (Fig. 1, right). All of the boards have been made by radial cuts through the stem. This is both time consuming and expensive.



Box 17.2 Figure 1 The three different kinds of methods for milling saw timber: plain sawn, quarter sawn, and rift sawn. *Source:* Mark S. Ashton.

Table 17.2 Leaf to sapwood area of select tree species from the US Pacific Northwest. Sapwood is the functional part of the stem that conducts water. Water-use efficient stems should have high sapwood area to leaf area ratio, meaning that a proportionally larger conductive system can supply a leaf area with water. Species that are from drier, more extreme sites, or that are more shade intolerant, have lower ratios than species from milder, wetter climates, or that are shade tolerant.

Species	Leaf area/sapwood area (m^2/cm^2)	Climate
Abies amabilis (Pacific silver fir)	0.64	Mild wet, shade tolerant
A. grandis (grand fir)	0.48	Mild wet, shade tolerant
A. lasiocarpa (subalpine fir)	0.78	Mild wet, shade tolerant
A. procera (red fir)	0.27	Mild, shade intolerant
Juniperus occidentale (western juniper)	0.18	Extreme desiccating, shade intolerant
Picea engelmannii (Engelmann spruce)	0.35	Mild wet, shade intolerant
P. sitchensis (Sitka spruce)	0.45	Mild wet, shade intolerant
Pinus contorta (lodgepole pine)	0.15	Extreme desiccating, shade intolerant
P. ponderosa (Ponderosa pine)	0.25	Desiccating, shade intolerant
P. sylvestris (Scots pine)	0.14	Extreme desiccating, shade intolerant
Pseudotsuga menziesii (Douglas-fir)	0.54	Mild wet, shade intolerant
Tsuga heterophylla (western hemlock)	0.46	Mild wet, shade tolerant
T. mertensiana (mountain hemlock)	0.16	Desiccating, shade tolerant

Source: Adapted from Waring *et al.*, 1982.

area, while long-lived species with large leaf areas have relatively lower sapwood areas.

There are also inherent ontogenetic changes in stem and crown physiology as a tree develops over time. As a tree grows from a seedling to sapling to pole to eventually a large canopy tree, its living body respiration increases relative to its leaf area (Fig. 17.5a). Seedlings that can withstand shade because of lower respiration rates, and therefore lower compensation points, become more shade intolerant with increased maintenance respiration when they grow taller and bigger in height and size. The compensation point is where the rate of photosynthesis equals the rate of respiration under a certain light intensity. At this point, the uptake of carbon dioxide through photosynthesis matches the release of carbon dioxide through respiration. Early successional species start off as seedlings with higher respiration maintenance rates, in large part because they are growing faster, and therefore are more shade intolerant than slower-growing, late-successional species. Differences in shade tolerance is similarly reflected in different species adaptations in crown morphology and leaf anatomy (Bond-Lamberty, Wang, and Gower, 2002; Poorter, Bongers, and Bongers, 2006) (Fig. 17.5b).

These relationships and differences among species at the physiological and morphological level also occur at the whole tree-crown architecture level. Crowns can remain the same shape as a tree grows. This is common among short-lived pioneers that have a spreading crown and leaf structure and among long-lived pioneers that have a compact crown. Late-successional species have crowns that change with time from columnar to shallow and expansive. The relationship between crown projection area and bole diameter of late-successional species therefore changes as the trees increase in height, and then mature and ascend into the forest canopy. Understanding the successional status of a tree species relative to other species is important in developing spacing guidelines for planting and thinning.

Stand Scale Patterns of Production

This section deals with tree growth (also called production or increment) at the stand level. Stands are collections of trees, but the measurement and analysis of stand growth per unit of land area reveals important patterns that cannot be seen from measurement of individual trees (Kelty, 1992; Reich *et al*., 1997; Waide *et al*., 1999). The basic biological measure of stand growth is the increase in biomass, generally in units of tons/acre/year (Mg/ha/yr). These units are in terms of oven-dried biomass to eliminate variations of moisture content that are not connected to growth.

The amount of sugar-producing foliage that a stand can maintain depends on species, and to a lesser extent, the ability of the soil factors to supply the foliage. Most evergreen species maintain more foliar surface than deciduous species, if only because the leaves persist longer than one growing season. Shade-tolerant species have more than the intolerants because their leaves can function at lower light intensity and thus form deeper crowns. Within a species, the total amount of foliage in a closed stand is much lower on a very poor site than on the best.

Poor sites produce less dry matter than good sites not so much because of major differences in the amount of foliage, but because the foliage cannot function as efficiently (Assmann, 1970). Deficiencies in the supply of nutrients and water from the soil can slow photosynthetic rates and the creation of new tissues. If water becomes unavailable because of depletion, low temperature, or soil-oxygen deficiency, photosynthesis must cease. High temperature can also cause stomatal closure and cessation of photosynthesis if evaporation exceeds the rate of water uptake.

The total photosynthesis of a forest stand (or of any ecosystem) is called gross primary production (GPP). It is measured in mass, which represents the glucose (carbohydrate) synthesized in photosynthesis. Some of the sugars produced by the photosynthetic process are used as the building blocks of cellulose and other molecules that make up plant materials. The rest is broken down through respiration to provide energy for the growth process and for maintaining the living plant cells. The annual increase in plant biomass is the net primary production (NPP), which is the GPP minus autotrophic (plant) respiration. Microbes, insects, and other organisms consume and decompose some of the plant matter that has been produced. They incorporate some of the plant matter into their growth and use much of it for their respiration; this is heterotrophic respiration. NPP minus heterotrophic respiration gives net ecosystem production (NEP), which is the increase in biomass of plants, animals, and microbes. This makes NEP difficult to measure. In most forests, biomass and respiration of organisms that consume plant material is quite small compared to the biomass and respiration of the trees and of the microbes in the soil and forest floor. NEP is often measured by NPP minus the rate of respiration from microbial decomposers (by measuring carbon dioxide). This assumes that the biomass of consumer and decomposer organisms doesn't vary over time, but of course it does vary with seasons.

The rate of GPP is dependent on the leaf area of the stand canopy. When measuring the leaf area per unit of land area, the measure is called leaf area index (LAI). Greater LAI provides the potential for high levels of GPP,

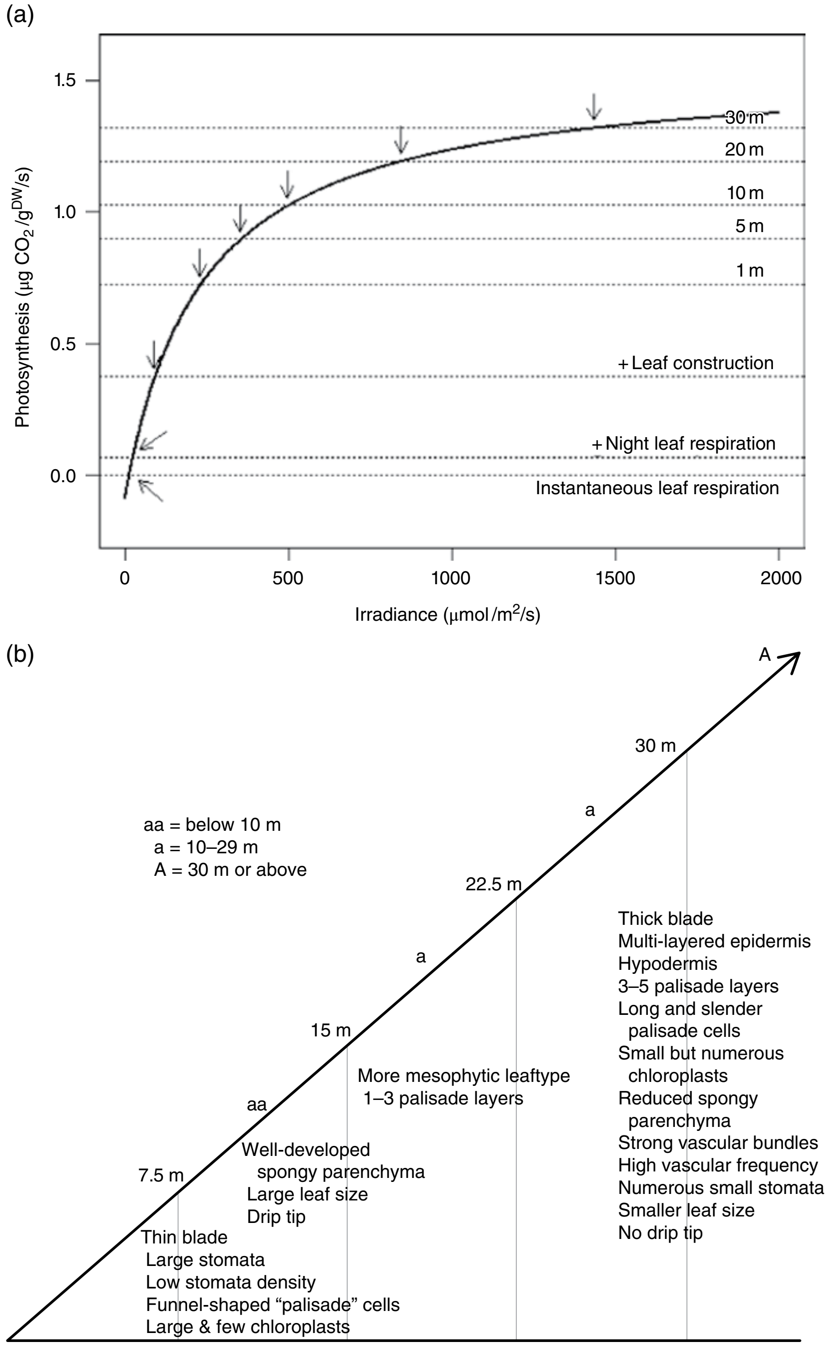


Figure 17.5 **(a)** A graph depicting photosynthesis, respiration, and compensation point with tree size (height) from seedling to canopy tree for a yellow-poplar (*Liriodendron tulipifera*). The curve is the instantaneous rate of photosynthesis (as measured amount of CO_2 assimilated per dry weight of plant per second) plotted as a function of irradiance (amount of sunlight as measured in μmoles/m^2/s). The horizontal dashed line at the bottom reflects the instantaneous rate of leaf respiration. The dotted horizontal lines represent the cumulative respiration rates first of night respiration, then leaf construction, and then of whole plant growth at various sizes (1–30 m; seedling to tree). The intersection between the rates of respiration for the different size classes and the photosynthesis curve are the compensation points (the point where respiration rate = photosynthesis rate). If a plant or tree is growing in a light environment where its rate of photosynthesis is below the compensation point then it will die. Shade-tolerant species have relatively lower compensation points in low light as compared to shade-intolerant species. This is particularly the case for seedlings, but as seedlings become trees, all species become more shade intolerant because their compensation points increase to match the increased respiration rates of larger individuals. *Source:* Givnish, 1988. Reproduced with permission from CSIRO Publishing. **(b)** A graphic illustrating change in leaf morphology with tree height from seedling to canopy tree. Leaves within all species change from thin and large to thick and small on progressing from understory to canopy conditions, but the more shade-tolerant species show the more dramatic changes. Fast growing shade-intolerant or drought-sensitive species will place less emphasis on expensive structures and thicknesses that make species withstand drought or shade. *Source:* Adapted from Roth, 1984 with permission from Springer.

but a supply of water and nutrients is necessary to convert the captured sun energy to glucose. Because the activities of fungi and insects are so variable, NPP is typically used to compare forest growth from different sites or ages. Often it is just a component of NPP, such as aboveground NPP or just stemwood. However, NEP is becoming an important practical measure because it is the plant biomass (live or dead) that remains at the end of a year, after decomposition has occurred. Since biomass is approximately 50% carbon, NEP is a good measure of carbon sequestration rate, which is increasingly becoming an objective of forest management. For inventories (as opposed to research where it is measured precisely but at high cost) some assumptions about soil decomposition must be made, with measurement of living and dead trees being the main factor (Whittaker and Marks, 1975).

One of the early studies of energy transformation and biomass production was conducted by Whittaker and Woodwell (1969) in a 45-year-old stand on a droughty site on Long Island, New York. This study provides an example of the details of basic annual forest production (Table 17.3a). In this case, with plenty of sunlight, GPP would have been limited by water supply. Note that more than half of GPP is used in plant respiration to grow and maintain plant cells. This is a common ratio (50–60%) in forests. Nearly half of this NPP (0.25 lb/ft^2/yr or 1195 g/m^2/yr), including a major part of that which went into such temporary tissues as leaves, was consumed by insects, fungi, and other dependent organisms. This left a net production (of new plant material remaining in the stand) of 0.11 lb/ft^2/yr (542 g/m^2/yr) (or less than one-fourth of the gross production). The proportion of new root tissue on this dry site is probably greater than it would be in forests on most sites. It is noteworthy that the shrubs and herbs grew more below than aboveground, but the trees did not. Only 0.03 lb/ft^2/yr (149 g/m^2/yr) of the annual tree production was in the form of main-stem wood; furthermore, the efficiency of conventional wood utilization is low in relation to the massive productivity of forests. Acorns, cones, and other reproductive structures accounted for 0.004 lb/ft^2 annually (22 g/m^2/yr). As is the case with most forests, the tree stratum produced much more substance than the subordinate vegetation (Table 17.3b).

Table 17.3 (a) Biomass and energy transformation of a pitch pine, scrub oak stand on Long Island, New York. (b) All of the net primary production (NPP) was the result of photosynthesis in only 384 g/m^2 of leaf tissue. The table shows the distribution of the net annual primary production (g/m^2) before the subtraction by consumption.

(a)

BIOMASS	tons/acre/yr	Mg/ha/yr
Gross primary production (GPP)	2647	5935
Plant respiration	1452	3255
Net primary production (NPP)	1195	2679
Animal and microbe respiration	653	1464
Net ecosystem production (NEP)	542	1215

ENERGY TRANSFORMATION	g/m^2
Total sugar produced (*gross primary production*)	2647
Respiration of the plants	1452
Remainder (*net primary production*)	1195
Consumed by insects, fungi, other organisms	653
Remainder (*net production of new plant material*)	542

(b)

	Net annual primary production (g/m^2)		
	Aboveground	Belowground	Total
Trees	796	260	1056
Shrubs	60	73	133
Herbs	2	4	6
Total	858	337	1195

Source: (a, b) Yale School of Forestry and Environmental Studies.

Where resources are non-limiting or less limiting (high rainfall year round, high sunlight, high-fertility soils) and where climates are cool but not frozen, NEP can be very large, as in the Pacific Northwest. Warm, wet climates (tropical wet forests) can have much higher GPP than cool, wet climates, but they also have higher plant and animal respiration rates making the NEP lower. These patterns in biomass and energy transformation can be seen and measured across landscapes that change hydrology (wet to dry slopes) and climate (warm- to cold-facing aspects) (Pregitzer and Euskirchen, 2004; Keeling and Phillips, 2007).

In general, evergreen forests and stands have greater NEP than deciduous forests and stands. Forests and stands with higher proportions of shade-tolerant species have higher NEP than those with higher proportions of shade-intolerant species (Pregitzer and Euskirchen, 2004).

Age-Related Changes in Stand Production

Gross and net production rates do not remain constant as a stand ages. Seedlings in a newly established even-aged stand will expand their crowns rapidly. As the

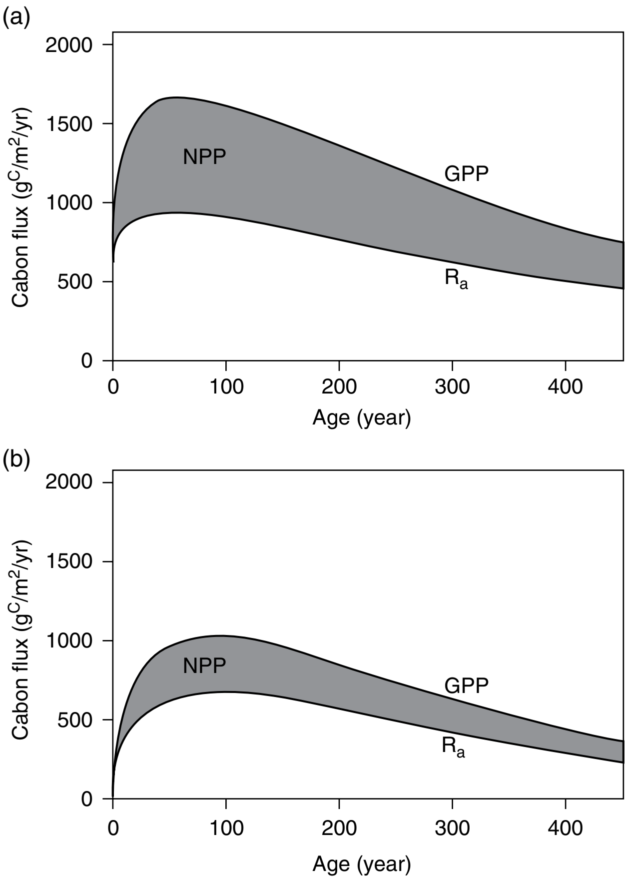


Figure 17.6 A graphic depiction of two scenarios for gross primary productivity (GPP), respiration maintenance (Ra), and net primary productivity (NPP) over time with stand development age. **(a)** Temperate forest. **(b)** Boreal forest. GPP first increases, then reaches an optimum, and then declines with age. Respiration maintenance follows the same pattern but its decline rate is less than that of GPP with age. This is a common pattern in all forest types and potentially relates to increased crown shyness from branch abrasion and/or increased moisture/nutrient limitations with age and size. *Source:* Adapted from Tang *et al*., 2013.

crowns fill in the gaps in the canopy, GPP will increase steadily and will reach a maximum at the time of canopy closure. After that point, GPP gradually declines. Plant respiration also increases with increasing GPP in the young stand, but then levels off at the time of canopy closure and remains constant or gradually declines (Ryan, Binkely, and Fownes, 1997) (Fig. 17.6). This pattern of GPP and plant respiration rate results in NPP increasing from stand establishment to canopy closure, and then declining with increasing age. This pattern of NPP is widely seen in forests with strong stressors that become more limiting with age (e.g., wind, ice, soil moisture, and soil-nutrient availability) (Fig. 17.6).

The mechanisms that control this growth pattern are not fully understood, and the growth pattern itself is somewhat surprising. Canopy closure occurs rather early in many stands. Why should young vigorous stands begin growth declines so early? This process has been observed in mixed-species and single-species stands; most studies of the process focus on single-species stands to reduce complexity and variability. The initial increase in GPP is clear, as leaf area increases because of crown expansion into openings among seedlings. GPP peaks and is maintained at a steady rate when complete canopy closure occurs but the subsequent decline of GPP has a number of possible causes. With many species, leaf area index (LAI) declines as a result of narrow gaps that develop between adjacent crowns (sometimes referred to as "crown shyness" or "canopy disengagement"). When the canopy first closes, branches interweave between adjacent crowns. As the trees grow taller, they sway in the wind and crown edges abrade, breaking off branch tips. The result is a canopy with many small permanent gaps that reduce the overall LAI.

In addition, other factors may arise that reduce the photosynthetic rate of LAI, rather than reduce LAI. In some combinations of species and sites, nutrients may become sequestered in standing tree biomass to the extent that there are insufficient soil nutrients available for root uptake. Nutrient stress would then reduce the photosynthetic rate. Similarly, hydraulic limitations in tall trees at older stand ages may reduce water availability to the canopy, again reducing photosynthetic rate, particularly on dry sites.

In forest management, much of the interest in stand growth is focused on the commercial part of the tree, which often is just the stemwood. Biomass production of stemwood follows the same general pattern as total NPP, with an increasing growth rate in young stands to a maximum at canopy closure and then a declining growth rate. However, the decline in older stands is more pronounced for stemwood than for NPP. The cause appears to be related to both the stand differentiation process and to the low priority in carbohydrate allocation to the woody parts of the tree, especially diameter increment (as described earlier in this chapter). The cause can be understood with the idea of crown efficiency of individual trees.

Crown efficiency refers to the rate of stemwood growth of a tree to its crown projection area or its leaf area. In a young even-aged stand before canopy closure, trees of a particular species will have similar efficiencies. After canopy closure, the stand will differentiate into a range of sizes from large dominant trees to small suppressed trees. Large trees develop large crowns that have many branches. Wood in general has low allocation priority, and branches (leaf-bearing stems) get first allocation of carbohydrate for growth and respiration, before non-leaf-bearing stems. Thus, bole-wood production declines in large trees. Suppressed trees have low photosynthetic

rates because of shading (low light levels) so they produce only small carbohydrate levels used mostly for replenishing foliage and fine roots; this in turn will cause very low allocation to stems. Suppressed trees often do not complete xylem growth down the stem. In contrast, a stand of similar-sized trees with moderate crown sizes will be most efficient in stemwood production per unit of crown. However, the largest trees in a differentiated stand are the most vigorous trees with the greatest absolute stemwood growth rate. These are often the trees that are favored for future growth in managed stands, but they have a lower stemwood growth rate per unit of crown area or leaf area.

It is important to note that the maximum time of stand biomass production is not really related to age, even though "age-related" is the term commonly used to describe the growth pattern. The pattern is controlled by the time of canopy closure. In natural stands, the timing of canopy closure is affected by initial stand density, site quality, and species. Foresters can change the timing by controlling early stand density, and controlling competing vegetation, or speeding up the process of canopy closure and increasing LAI by using fertilization.

Measuring Growth

Traditionally in forestry, there are three measures that have been used to gauge stemwood growth of individual trees and stands: (1) **mean annual increment (MAI)**; (2) **periodic annual increment (PAI)**; and (3) **current annual increment (CAI)**. Measures of volume increments of the stem are usually the norm but it is easier to calculate DBH as a proxy. Periodic or current annual increment area is a better measure of growth than diameter increment because of the increase in bole diameter over time.

Mean annual increment is the average annual growth increment over the total age of the tree or stand. For example, a tree that is 15 inches (38 cm) DBH, and is 15 years old has an MAI of 15/15 = 1 in/yr (2.5 cm/yr). Periodic annual increment is the average growth increment over a period of years. It is usually taken to be the most recent 5 years. Current annual increment is the growth for the most recent year of growth.

The point where the MAI and PAI meet is referred to as the biological rotation age (Fig. 17.7). It is always where MAI reaches a peak. This is the age at which the tree or stand would be harvested if the management objective is to maximize long-term yield. It is a key value for determining how much can be harvested annually if a forest is managed to produce a sustained yield of timber and how long the rotations should be to maximize production. It is also important to recognize that stand-level averages of MAI and PAI do not reflect individuals but the stand average. Individuals can have very different patterns of growth because they differ by species and by crown and rooting position within the stand.

It is extremely difficult to determine MAI for uneven-aged stands since they have no single age. However, every year, the theoretical balanced all-aged forest would have a CAI virtually equal to the peak MAI of an even-aged stand *of the same species grown to the same rotation age on a similar site.*

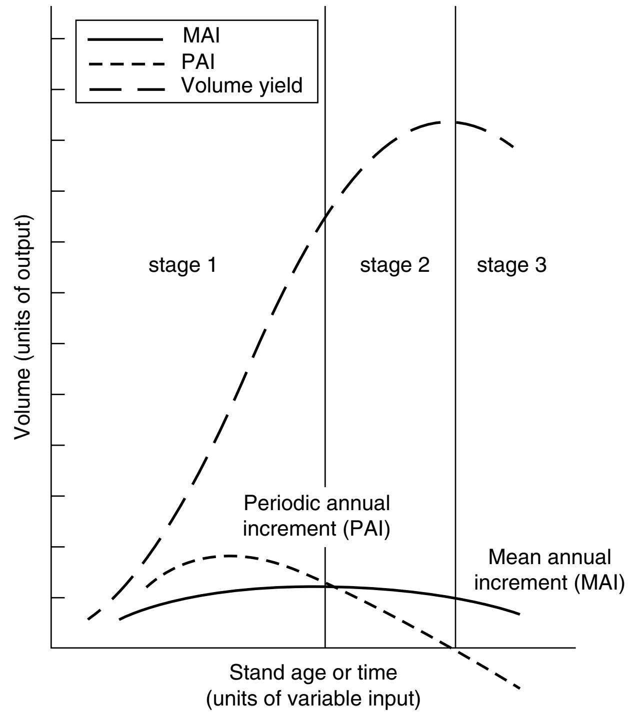


Figure 17.7 A graph depicting the stand-level mean annual increment (MAI) and periodic annual increment (PAI) over the course of development. The long-dashed line indicates the volume yield over time. The maximum point on the curve of PAI is the same as the inflection point on a graph of yield versus time. The inflection point is the point corresponding to the fastest change in yield. In most circumstances the most economic rotation period (highest net present value) is always shorter than the biological rotation. The culmination of MAI is often regarded at the biological rotation of a stand (as depicted by the line demarcating stage 1 from 2). The curves originate from zero because they are based on total dry-matter production. If they were based on board-foot volume with some large minimum top diameter for logs, the origins of the curves and their peaks would shift far to the right. If the measurement units define product objectives, the age of maximum MAI is the optimum rotation length where the objective is to maximize production from a limited land base. If the PAI of a given stand exceeds the simultaneous MAI, this means that the stand has not yet reached the culmination of MAI; one may also make an educated guess about the amount of MAI, and the time of its culmination. PAI becomes negative after the age when decay and mortality becomes equal to growth, as in very old stands. MAI would decrease to zero only when the very last tree of the initial stand was gone. *Source:* Mark S. Ashton.

The Effect of Thinning on Stand Production

The main objective of thinning is to increase the yield of usable wood by increasing the size and quality of individual trees. However, it is also important to understand the effects that thinning has on the stand-level production. There has been considerable confusion about this matter, with much of the confusion being centered on the graph in Fig. 17.8. This graph shows the hypothesis that was proposed in the early 20th century, based on early European thinning experiments and theoretical considerations of tree physiology of Wiedemann (1925), Moller (1922), and Langsaeter (1941) (see review by Skovgaard and Vanclay, 2008).

The Langsaeter curve is a part of the idea of rules and laws that always hold true. This graph has been accepted by many foresters and published in many books, and has an important impact on management. It indicates that foresters have considerable flexibility in choosing thinning intensity to produce larger individual trees, without loss of overall stand-level production. However, it does not match reality. Instead, it is now apparent that these patterns are responses to variations in species and sites, and their interactions.

Before analyzing the evidence regarding the thinning–production relationship, it is necessary to review the methods. The measures of volume production can vary, but nearly all studies have used merchantable wood volume. European studies follow a standard that includes all aboveground wood (stems and branches, with bark included) that is larger than 3 in (7 cm) in diameter. By using this low diameter specification, most of the wood is included. Specifications for studies in the US and other regions vary greatly.

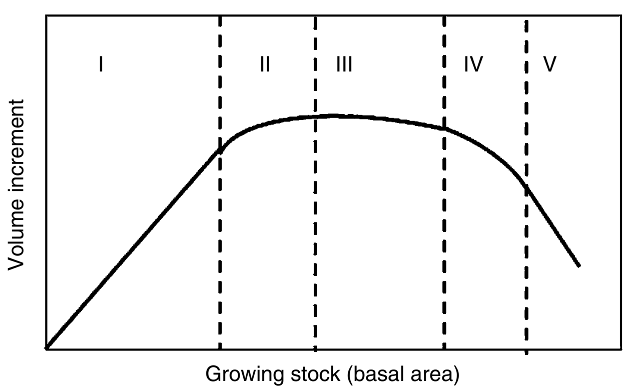


Figure 17.8 Langsaeter's curve. The hypothesized pattern of stand volume growth at different levels of stand density, as measured by basal area. This pattern (often called Langsaeter's curve) is no longer accepted as the pattern for most species or sites. *Source:* Yale School of Forestry and Environmental Studies.

There are practical reasons for setting these limits, but they are problematic, and may cause some of the conflicting evidence about the relationship of stand density to production. In high-density stands, diameter growth is slower for all stems and branches. Therefore, dense stands will have a smaller proportion of the total amount of wood counted in the assessment of production. This is especially important in the very dense stands used in European studies. Total wood biomass would be the best biological measure. It would clear up some of the confusion, but use of merchantable volume has the advantage of keeping a focus on yield. Having both measures would be ideal.

The studies that have been conducted to test the so-called Langsaeter hypothesis consist of even-aged stands of a single species (or predominantly one species). Plots are thinned to varying densities, as measured by basal area (BA). The densities are often described as a percent of the mean BA that occurs in unthinned stands. One requirement for this kind of study is to specify the sizes of trees to be removed within each plot. As described earlier in this chapter, trees in different crown positions have different growth efficiencies. Overtopped trees have the lowest efficiencies. If thinning experiments do not carefully remove trees of similar crown positions for each thinning intensity, then the results will be difficult or impossible to interpret. The response of trees of different crown status will vary greatly after thinning. Most studies have used low thinning, which selects the smallest trees first for removal, and then moves up in size until the desired stand density is reached. Useful comparisons could not be made if large trees were cut, leaving the low-efficiency small trees to respond to release from thinning.

The initial reinterpretation of the evidence from European studies was from Assmann (1970), who provided an early form of meta-analysis in his review of the early experiments. In addition, a number of studies in the US have been conducted that reflect current thinking (Fig. 17.9) (Long and Smith, 1990; Jokela, Dougherty, and Martin, 2004).

The main pattern is of consistent decline in volume production with increase in thinning intensity. The slope and curvature of the line differs among species, but the declining trend is consistent. The reductions in volume increment are shown in Table 17.4, using the stand density of 50% of the unthinned basal area for each species.

The major consequence is that thinning to promote larger individual tree size is done at the expense of losing stand volume growth. With the Langsaeter hypothesis, it appeared that there was no tradeoff between individual tree growth and stand growth, but there actually was, and is, a tradeoff.

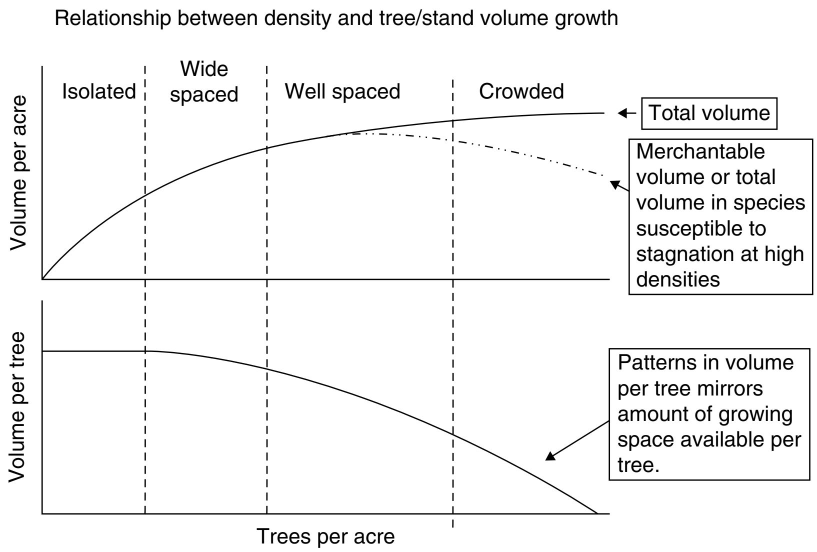


Figure 17.9 These graphs should replace the flat line hypothesis and Langsaeter's curve. Top: the general trend shows that stand volume increases with stand density and basal area to reach a maximum allowable density. Bottom: individual tree volume dramatically declines with increased stand density because of increasing competition for growing space. Evidence supports these trends rather than the Langsaeter curve in Figure 17.8.
Source: Adapted from Smith *et al.*, 1997 and from Daniel *et al.*, 1979.

Table 17.4 Gross woody volume reduction from thinning by select timber tree species.

Species	Volume reduction at 50% BA compared to unthinned BA	Reference
European beech	−10	Assmann, 1970
Norway spruce	−10	Assmann, 1970
Scots pine	−25	Assmann, 1970
Sessile oak	−25	Assmann, 1970
Douglas-fir	−25	Curtis, 1967
Eastern white pine	−30	Seymour and Smith, 1987
Loblolly pine	−15	Nelson, 1964
Red pine	−20	Martin and Ek, 1984

Source: Yale School of Forestry and Environmental Studies.

The second pattern occurs on dry sites, as noted by Assmann (1970). Overtopped trees in these stands are using water and nutrients, but they produce very little wood increment. They are just surviving, renewing foliage and roots, but not increasing in wood. By removing these trees, resources now made available belowground (water and nutrients) are used by trees in upper canopy positions. Growth then increases with light thinning because the canopy is not opened by the removal of the understory trees. With greater thinning, the negative effects of the growth of canopy opening outweighs the more efficient use of soil resources, and the declining pattern occurs. This effect has been observed in oak stands in the eastern US. In the removal of understory trees on dry sites (light, low thinning), growth increases in the overstory, but no overstory increase occurred in areas with higher precipitation (Breda, Grainer, and Aussenac, 1995). The same pattern occurred with understory removal of hardwoods growing beneath pines in dry and moist sites (Kelty, Gould, and Twery, 1987).

There are a number of reasons why the Langsaeter curve was accepted for so long. The range of thinning in many early studies was limited, starting with very dense unthinned stands and reducing to 80% of BA. Many research plots in the early days were not replicated and there was likely no consistent response across different studies with these limitations. Also, Moller was influenced by the relationship of respiration to stem surface area; this suggests that thinning will reduce respiration which will compensate for opening of the canopy, but, as described earlier, maintenance respiration is not great enough to make this balance (Moller, 1922). It should be noted that if light, low thinning is being used, especially for shade-tolerant species, the change in volume increment is not very great, and can be essentially flat over 80–100% of BA. Finally, it should be noted that repeatedly removing the largest trees by thinning will reduce the volume more drastically than is found in these studies, which were almost all low thinnings.

A study of loblolly pine (Nelson, 1964) shows the impact of site. Unthinned stands develop much higher volume growth and higher BA on good sites. This demonstrates the importance of not relying only on BA percent. In retrospect, there does not seem to be a reason

to have thought that all species on all sites would follow a similar quantitative response to thinning.

The Effect of Thinning on the Economic Yield of Stands

Practical understanding of thinning procedures depends on knowing how they can be applied to increase the economic yield, even though they do not substantially increase, and may even slightly decrease, gross production. The general approach is to allocate the production to some optimum number of trees of highest potentiality to increase in value; the other trees are systematically removed in such a sequence as to obtain maximum economic advantage from them. The various advantages that can be gained are as follows:

1) salvage of anticipated losses of merchantable volume;
2) increase in value from improved diameter growth;
3) yield of income and control of investment in growing stock during rotation;
4) improvement of product quality;
5) opportunity to change stand composition to prepare for the establishment of new crops;
6) reduced risk of damage or destruction by insects, disease, fire, or wind.

Salvage of Anticipated Losses

The gross production of wood by a stand should not be confused with the actual yield in terms of usable volume removed in cuttings. Not all the cubic feet of wood produced by the growing stand remain stored on the stump until the end of the rotation. In fact, a high proportion of the total production will be lost from death and decay of the large numbers of trees that do not survive the struggle for existence. From the economic standpoint, any part of this perishable volume that can be salvaged by removing doomed trees in thinnings represents an increase in the quantitative yield of the stand. However, at least in the early years, much of this material is not harvested because harvesting and transportation costs exceed the value of the trees.

If a typical stand is grown on a rotation long enough to produce trees of conventional sawtimber size without thinning, as much as one-third or even one-half of the potentially merchantable cubic volume may be lost to suppression. This kind of loss can be reduced by ending rotations when such mortality becomes serious, but this approach makes it hard to get trees of the diameters often desired. Diameter growth can be increased by widening the initial spacing of the stand, but this maneuver prevents suppression loss, partly by leaving growing space vacant and thus merely preventing the production that would become loss. Thinning is the best solution to this dilemma and is therefore practiced whenever other considerations do not preclude it.

Thinnings designed to anticipate and salvage losses from natural suppression are the only proven means, other than site improvements, of increasing the yield of total cubic volume or tonnage from a stand. Only part of the prospective losses can be recovered unless stands are annually gleaned for dead and dying materials no matter how small. Unless the site is ameliorated such as by fertilization, the practicalities of timber harvesting dictate that the harvested yield can be increased only by decreasing the gross production of the stand.

Not all of the material removed in anticipation of loss will need to come from small trees of the suppressed and intermediate crown classes. By using crown and selection thinning, it is possible to take out part of this volume in larger trees, thus forestalling the death and stimulating the growth of their subordinates. Selection thinning must be used carefully in this way because frequently the lower crown class trees will not respond well to release, and the overall growth of the stand will be reduced.

Increase in Value from Improved Diameter Growth

Up to this point, the discussion of the effect of thinning on the quantitative yield of a stand has dealt mainly with production of cubic volume. However, not all units of cubic volume of roundwood are equally valuable; those that come from large trees are generally of greater value than those from small trees. One of the most important objectives of most kinds of thinning is to reduce the stocking of a stand so that it eventually has fewer trees, but of larger average diameter than it would without thinning.

The most general reason for the greater unit value of trees of large diameter is that the cost per unit value of ultimate product is less for processing them than for small ones (Fig. 17.10). This relationship applies to the cost of handling each tree or log individually during harvesting and subsequent processes. The monetary return for growing a tree, stumpage, is the difference between the value of the ultimate unit of product and the cost of harvesting, transporting, and processing it. The forest owner who grows 100 units of cubic volume in fat trees saves handling costs for the buyer and is thus entitled to a higher price than one who grows 100 units in a greater number of slender trees. Of all the economic reasons for thinning, this one is usually the most important.

A second reason for trying to improve diameter growth is that wood quality usually increases with tree diameter. This is mainly because the outer rind of wood has fewer knots and grain irregularities than the central

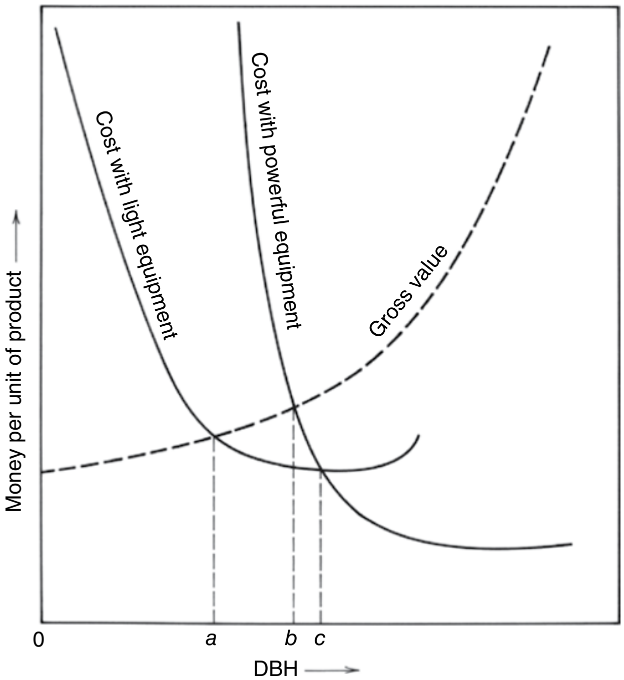


Figure 17.10 The effect of the diameter of a tree on the cost of processing it, and the value of the product, per unit, when the harvesting and processing are done with two different sets of equipment. The set of light equipment is low in capacity and cost; the powerful equipment is high in initial investment and hourly operating cost. Points a and b are the smallest diameters at which it becomes economical to use each set of equipment. For trees larger than diameter c, it would be logical to use the more powerful set. Net value at any diameter is the vertical distance between the appropriate curve of cost and that of gross value. Note that certain costs, such as those of roads or of handling trees collectively in bundles, are not affected by tree size. The curve of gross value would be nearly horizontal for such products as fuelwood or that which is chipped for pulp or other reconstituted products. Gross value can also decline with increasing tree size if the incidence of rot or similar defect increases with age or size. Note that the ideal thinning program would be one in which trees are caused to move as swiftly as possible into diameter classes that can be harvested most profitably and also with equipment appropriate to those sizes. *Source:* Yale School of Forestry and Environmental Studies.

core; ordinarily, it also has superior anatomical and mechanical properties. The outer wood is usually stronger, more easily worked, longer-fibered, less subject to warping, and in most ways much easier to use than the inner wood. With some species, the inner wood improves when it turns to heartwood, but this change also depends on diameter growth. The more outer wood that can be added by increasing diameter growth, the greater is the inherent value of the wood.

One of the most common and valuable ways of using trees is as lumber or solid-wood products. There is probably no other way of producing structural materials that is more economical of the world's energy supply. Unfortunately, it is not correspondingly economical, either of the wood itself or of the time required to grow trees of suitable sizes. Both of these problems can be mitigated by thinnings designed to grow trees of larger diameter in shorter time.

The waste of wood in lumber production is in the sawdust, slabs, and edgings generated when round stems are sawn into square-edged boards. Given the ordinary requirement that boards be of certain minimum thicknesses, the proportion of wood that is wasted is greater in trees of small diameter than in large ones. In fact, there is usually some minimum diameter of stemwood below which the material is simply left in the woods; the proportion thus abandoned in severed tops is also inversely related to diameter. One exception is the production of small-dimension products which often results in utilization to a very small minimum diameter. In this case, a large number of small trees will have less total branchwood than a smaller number of large-diameter trees.

The board-measure log rules that are used in North America are, in effect, computational devices designed to estimate the volume of lumber that will remain after round logs are sawn into square boards. One cubic foot of wood (0.028 m^3) could be converted into 12 board feet (0.005 m^3) only if a tree were a square timber throughout its length and could be sliced into boards without sawdust or other waste. Cubic volume is, in other words, round and not square. The ratio of board feet to cubic feet ranges from roughly 5 in trees about 8 in (~20 cm) DBH to a nearly stable value of 7, or slightly more in trees that are more than 20 inches (~30 cm) DBH. If trees are grown for lumber and the cubic volume growth is fixed, this difference in proportion of waste is another reason to seek improved diameter growth. Even if the waste is used for reconstituted wood products, loss of potential value still takes place.

Not all units of board measure are equally valuable. Those that are in wide boards are worth considerably more than those in narrow ones. This is yet another advantage that accrues to improved diameter growth.

Merely because the calculations are easier, the results of thinning trials are often interpreted in terms of common mensurational units, especially cubic volume, without any consideration of the distribution of diameters in the stands. In fact, many thinnings have purposely tried to duplicate the distribution of diameters before and after thinning for statistical convenience in determining volume growth changes. The purpose of most regimes of stand management is to maximize the production of net value and not just volume.

Rough comparisons can be made between possible treatments by observing the distribution of numbers of trees or of volume by diameter classes. Another simple test parameter is the average diameter of a fixed number of the largest trees per unit area, such as the 100 largest/acre (ha). It must be borne in mind that the average

diameter of a whole stand is automatically increased by removing some of the smaller trees.

To reap the rewards of cutting large trees late in the rotation, it is necessary to cope with the high cost per unit volume of harvesting and utilizing small trees in earlier thinnings. This difficulty can be mitigated partly by using different equipment and logging methods for the small trees than are later used for the large. The kind of equipment that is most efficient for handling final crop-trees is usually not the best for the thinnings; such equipment is ordinarily heavier, more cumbersome, more costly, and more expensive to operate for a given length of time.

The problem can also be evaded by delaying the thinnings until the trees to be removed are grown large enough to handle economically. Another evasion is to confine the first removals to any large- or medium-sized trees of poor potentiality and to ignore the small ones until they become larger. Trees that are destined never to be worth harvesting can be either left to die of suppression or killed by the cheapest means available.

The ideal solution is to manipulate the equipment and sequence of thinnings so that the equipment is matched with the sizes of trees to be removed, and as many trees as possible are cut when they have grown into the range of diameter that can be harvested efficiently. The objective should be to maximize the total value from harvesting the entire crop of one rotation rather than to minimize the cost of each separate operation in the whole sequence of cuttings.

Increase in stem diameter is so advantageous that it is generally best to thin stands down to the lowest density that will not cause poor tree form or other unacceptable side effects. Deliberate sacrifice of production of gross tonnage or total cubic volume is often desirable; sacrifice of production of merchantable volume may or may not be desirable, depending on the relative merits of growing large trees and securing a large total yield of wood of any sizes. Some countries are sufficiently concerned about maintaining high wood production such that they prohibit thinning so heavily that yield of merchantable cubic volume is sacrificed. The stand structures that result from heavy thinnings sometimes have other advantages, such as foraging areas for the red-cockaded woodpecker in the southeastern US and the maintenance of hardwood browse for large herbivores in many areas.

Yield of Income and Control of Investment in Growing Stock During Rotation

An unthinned crop of trees is an asset that increases in value throughout the rotation but remains frozen under passive management. No cash income is realized, yet carrying charges accumulate that must be paid for by the crop. After some trees have become merchantable, thinning can become a form of continual asset management.

The early returns from thinning will lead to longer rotations if the overriding goal of management is timber. Money from the early part of the rotation is worth much more than income received later in the rotation, because of the compounding effects of discount rates. The periodic removal of the poor earners and encouragement of the good earners is a means of decelerating the speed at which the growth rate of the overall stand value inevitably declines. The rate declines between thinnings and can be elevated again by each thinning. When it becomes impossible to restore the rate to the desired level, according to this mode of analysis, it is logical to replace the stand with a new one and thus end the rotation.

In applying this idea, it is best to allocate growing space to the trees that earn the most. This allocation requires estimates of the earning capacity of trees of different classes of diameter, crown class, and stem quality. Once a few calculations are made and the basic relationship between tree characteristics and earning capacity is formulated, it is then necessary to use intuitive judgment in determining which trees to cut or leave because the detailed computations are too complicated to apply tree by tree. It is especially difficult to take differences in tree quality into account. The easy assumption that all trees of the same diameter in a stand are of the same value can impair application of the principle.

Thinning can be applied in such a manner as to reduce the investment in growing stock and increase the value of gross growth by removing trees of low earning potentiality and increasing the growth of those of high potentiality. Because growing stock can be reduced without greatly reducing volume growth, this becomes a way of eating one's cake and having it too.

In whole forests that are young and immature because of earlier heavy cutting in a locality, thinnings and other intermediate cuttings may provide the only source of income for long periods. Thinning helps meet two financial tests that are often applied to long-term investments in timber production. Both tests involve compound interest and affect decisions about rotation length. Consequently, the two different tests often get confused with each other.

The first test requires an adequate rate of compound-interest return on all out-of-pocket costs of establishing the crop and carrying it to maturity. The second test requires that the rate of interest earned on the stumpage value of the trees or stands will not fall below some desired rate. The rate demanded under the first test, which involves whole rotations and hard cash, may be higher than that of the second, which operates over shorter periods and merely involves income temporarily forgone. These are separate tests, and the choice must be made as to which analysis should be used for thinning decisions.

In the first test, the cost of establishing a stand and all subsequent costs are carried at a compound interest rate

until the end of the rotation. Thinning helps meet this test by providing income during the rotation which is also compounded to the end of the rotation. By the reckoning involved, the money received at age 20 may be worth twice that at age 35. The compounded costs of stand establishment early in the rotation can be offset by early thinning returns rather than letting them mushroom until the end. If the thinning enables trees to grow larger and more valuable, or increases the total yield, the net income against which the charges can be made is increased. If these improvements make it financially prudent to have longer rotations, the average annual expense for regeneration in the whole forest is reduced, and so the overall result can be still further improved.

The second test involves the crucial task of improving the return on the large investment represented by the liquidation value of merchantable growing stock in managed forests. For example, if an owner requires a rate of return of 8%, each dollar left in growing stock at the beginning of the decade must grow to $2.16 in value during the decade to justify having left the tree or stand. In this test, unlike the first, any money invested in growing the tree does not count; only that money for which it could have been sold at the beginning of the period is considered.

The second test embodies one of the most useful ways of determining which trees to cut and which to leave in thinning. Those trees that cannot be made to increase enough in value to yield an acceptable rate of return on their own value are removed. Those that can are not only left but they are also granted enough additional growing space that the compound interest that they earn is increased. The trees most likely to continue yielding the desired rate of return for the longest time are those of highest quality and rate of growth. In a pure application of this approach, the first trees to be cut would be those of low quality or slowest growth, although they would theoretically not be cut until they had acquired a positive value.

Regardless of how rotation length is determined, thinning provides ways of extending rotations and also of lending some flexibility to their control. The rotation necessary to grow trees of a given size can be shortened; larger and more valuable trees can be grown on rotations of fixed duration. Short rotations do not necessarily have the financial values that are so often ascribed to them, especially if all of the financial factors involved are considered. If thinnings have produced enough revenue to amortize establishment costs, yield an adequate income, and maintain good rates of growth, there may be little need to rush into the risk and expense of starting a new crop that will be some years in regaining full occupancy of the site. The forest manager who refrains from thinning may be condemned to short rotations, frequent regeneration problems, and limited opportunity to maneuver to meet all sorts of emergencies and changes in markets or management objectives.

Improvement of Product Quality

The value of a fixed total production can be enhanced simply by favoring the trees of best potential quality and discriminating against the poor ones. This effect of thinning on wood quality is vastly more important than any other. The superior diameter growth induced by thinning usually improves wood quality because the large trees tend to be of better quality than small ones. The general effect of thinning on wood quality is not harmful, in spite of some opinion to the contrary.

Control of Stand Composition and Effects on Regeneration

The opportunity to intervene in the development of the stand during the rotation produces a number of other economic benefits. It enables continuing control of undesirable species that were not eliminated during the period of regeneration. If mixed stands of dissimilar species are being deliberately maintained, thinning may represent the only means of taking adequate advantage of those species that tend to mature earlier than the major components. The long period of control over stand composition enables the forester to prepare for natural regeneration by reducing the seed source of undesirable species and fostering that of the good. Thinning also builds up the physiological vigor, mechanical strength, and seed production of the individual trees of the final crop, so that there is wider choice among methods of regeneration cutting. Unthinned stands are likely to have to be replaced during an abbreviated period of establishment, even when more gradual replacement might enable greater use of the financial potentialities of the crop.

Reducing Risk

Thinning can reduce the risk of the stand being destroyed or reduced in value by a variety of causes. One of the main effects of thinning is to increase the vigor of the trees by giving each tree more growing space. Increased vigor increases the tree's ability to respond to most insect attacks. Production of secondary compounds helps protect the tree from many types of herbivory, and the additional vigor allows those trees capable of a second flush of foliage to recover from defoliation. More vigorous trees are also able to withstand reductions in photosynthesis without succumbing to the overriding needs of respiration.

Thinning also increases protection from abiotic agents. Salvaging potential mortality reduces the fuel load that leads to catastrophic fires. Thinning leads to reduced height/diameter ratios and greater wind firmness.

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18

Post-Establishment Tools in Silviculture

Introduction

This chapter introduces the tools and techniques for controlling growing space in order to change, inhibit, or facilitate the dynamics of forest vegetation. In a sense, this chapter is designed to complement Chapter 7 on site treatments. However, the focus in this chapter is less on preparing, protecting, and changing the site for regeneration, but rather on the techniques that can be used to influence growth and composition of existing vegetation to achieve desired outcomes. The topics covered in order are: (1) girdling and cutting, (2) herbicides, (3) prescribed burning, (4) fertilization, and (5) irrigation. Pruning and release cuttings are covered in the next chapters (Chapters 19 and 20 respectively). All of these tools can be used in stands that have established plantings or natural regeneration.

Cutting and Girdling

Cutting and girdling are two methods of removing larger sized trees over topping saplings and vegetation that are being suppressed. Both techniques can promote re-sprouting of the target stems so care must given as when, how, and what species should be treated.

Cutting

The felling of large, undesirable trees without utilizing them (called **liberation cutting**) is the most expensive method. The felling may also result in far more damage to the young crop than would occur if the trees were killed by girdling or other methods and allowed to disintegrate in place. Therefore, trees are felled, limbed, and left on the ground only where absolutely essential. This may be desirable where standing dead trees create a serious fire hazard. Cutting may be necessary along roads where falling limbs and snags are likely to be a danger.

Girdling

The traditional method of killing trees without felling them is called **girdling**. This involves cutting into the bark, phloem, and cambium, around the entire trunk of the tree. Usually the cut goes a short distance into sapwood (xylem), to make certain that the thin layers of phloem and cambium have been cut. The sugars, inorganic nutrients, and other materials can still be carried up in the xylem to the crown. The sugars will still be produced by photosynthesis in the foliage, but they cannot be translocated down to the roots because of the cutting of the phloem. It may take more than a year for the roots to be exhausted of their own stored carbohydrates. If all or most of the sapwood were cut, the death of the crown would become more certain because of the reduced flow of water and inorganic nutrients to the roots. However, the vigor of sprouting increases as a result because the crown dies quickly, and roots still have stored carbohydrates to send to the sprouts.

If any vertical strips of cambium are left intact, bridges of callus tissues are almost certain to form across the girdled ring. This can happen even if the cambium is completely severed. Therefore, it is desirable to cut out chips of bark and sapwood so that the cambium is actually removed in a visible ring, rather than merely severed in a single cut. Trees that have deeply infolded bark around frost cracks or other deformities are almost impossible to kill by girdling. Mortality may also be reduced if the girdled trees are connected to other trees of the same species through root grafts.

Girdling can be done with axes or chainsaws. In **single-hacking** or **frilling**, a single line of overlapping ax cuts is made through the bark (Fig. 18.1). This method is seldom effective by itself because the cuts usually heal, but it can work if herbicides are sprayed into the cuts (see the chemical girdling section on herbicides). For large trees, a chainsaw is used to cut into the bark, completely around the tree. Two more similar cuts are made about 6 in (15 cm) above or below the first cut; these are to make certain that the tree will not survive.

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

The most common and effective method of girdling with axes is **double-hacking** (Fig. 18.1). In this method, a horizontal line of chips is removed by striking two downward blows; the second is made about 2 in (5 cm) above the first so that the chip of bark may be pried entirely out of the cut with a twist of the ax handle. With this technique it is easy to see that no strands of inner bark and cambium remain.

The **peeling** method is quite effective, but it can only be used when the cambium is highly active and the bark is "loose," as often found in spring and early summer in temperate climates. Peeling will not work if the bark is "tight." With this technique, two continuous cuts are made around the tree, at least 8 in (20 cm) apart. The cuts are just deep enough for the bark to be peeled off between the two cuts. Peeling is the best technique from the standpoint of interrupting the phloem without halting the upward flow of stored substances from the roots. The reason for removing such wide strips is that the cambium can sometimes survive and regrow unless there is thorough exposure to desiccation.

Girdling is much less effective than herbicides in preventing sprouting. This may be an advantage if the purpose is to increase the supply of food for browsing herbivores. If sprouting is not wanted, then girdling is best reserved for non-sprouting species or stems too large to sprout. For trees of sawlog size, girdling can be as effective as injecting herbicides. It can be done effectively on trees as small as 4 in (10 cm) diameter at breast height (DBH), although herbicides are better for these medium-sized trees. Below that diameter, cutting is easier, cheaper, and safer, but herbicidal treatments are usually superior to either (Wagner and Rogozynski, 1994).

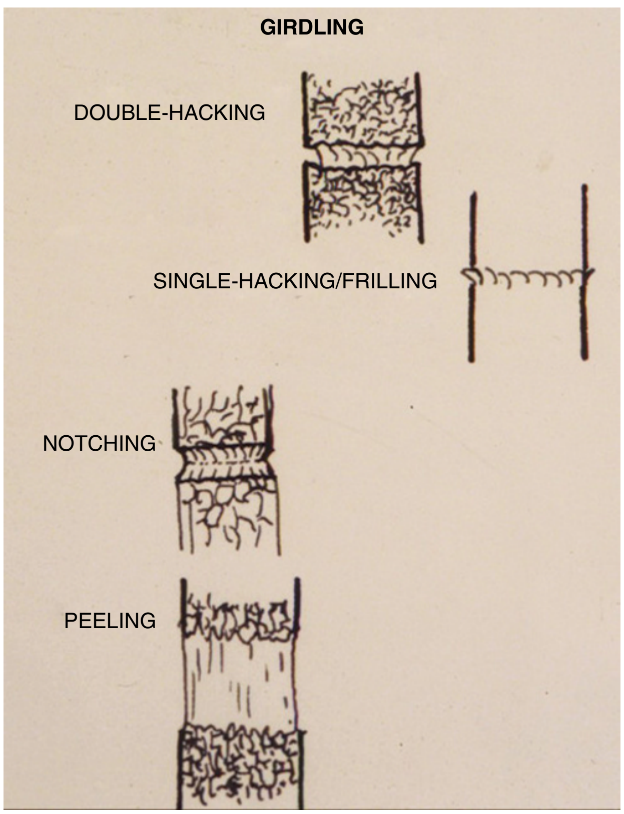


Figure 18.1 Depictions of double-hacking, single-hacking/frilling, notching, and peeling. *Source:* Mark S. Ashton.

Use of Herbicides

Herbicides are used in forestry for: (1) releasing desirable seedlings and saplings from competing plants; (2) clearing vegetation for site preparation; (3) killing non-native invasive plants; and (4) removing larger trees in precommercial thinning and liberation operations. Most of the chemical compounds that are used for these purposes were designed for agriculture. More than 90% of herbicides are used in agriculture, so that is the only market for which new herbicides are developed. Much of the rest is for managing turf grasses in golf courses and lawns. Most of the weeds in farm fields are herbaceous, which is why they are called herbicides. Foresters then must make them work for silvicultural objectives.

The main difference for herbicide use in silviculture is that many of the plant species that are to be killed are woody plants. One of the important uses of herbicides that is unique to forestry applications is to kill broadleaf species while leaving conifers unaffected. Another specific use is to kill particular tree species that are mixed within a stand to favor other trees, which is another unique forestry application.

There is considerable concern about the use of chemicals for killing plants in general, especially with forestry, where more regulations have been implemented compared to any other sector. This is ironic because agriculture produces the food we eat, and we come into direct contact with lawns. The concern with forestry generally is rooted in the fact that most forests are of natural regeneration origin and are perceived as wild and/or natural, with much greater importance for water sources, wildlife, and recreation, than agriculture or horticulture. Conventional views believe that recreation in the forest should be without artificial chemical intrusion, whereas recreation on an intensively managed golf course or soccer field seems fine. Thus, it is wise to be as conservative as possible in the use of herbicides for whatever purpose in mind. There still are no data to evaluate the long-term impacts of herbicide use because they have only been in use for about 30 years, and have been widely used only in the last 20 years. The most blatant abuses of herbicide use are by the homeowner, urban municipalities, and recreation organizations and their widespread and repeated application on lawns, streets, and golf courses.

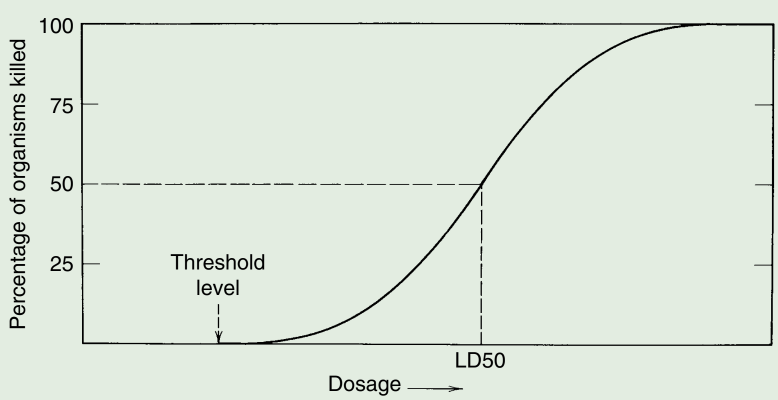
In forestry, if and when they are used, they are usually used only once or twice (site preparation or release treatment) over many years in a plantation, and in most places and circumstances in forestry they are not used at all. For example, in a normal year, the 190 million acres (76,923,000 ha) of the National Forest System uses herbicide application on about 182,900 acres (74,464 ha) (including rangeland) or about 0.09%, mostly to treat invasive weeds. Likewise, on the 160 million acres (65 million ha) of private lands in the southern US, about 1.5% is treated annually mostly to release pine plantings from hardwood competition (Shepard, Creighton, and Duzan, 2004). All herbicide sales and uses are regulated by the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) which also provides a comprehensive system of testing for toxicity (Box 18.1). However, further research does need to be done, given the focus on testing of: (1) only a small number of species; and (2) only the active ingredients of herbicides and not the inert components. For example there is now some evidence that the inert chemicals used with some herbicides can be carcinogenic (Peixoto, 2005). Further research also needs to be done on testing of mixtures of herbicides commonly applied in forestry operations (Shepard, Creighton, and Duzan, 2004). Given the long-term unknowns of herbicide use, the take-home message here is to use herbicides sparingly and in a conservative manner, and if at all possible avoid their use.

There are many more comprehensive accounts of these matters, such as those of Newton and Knight, 1981; Klingman, Ashton, and Noordhoff, 1982; Beste, 1983; Walstad and Dost, 1984; and Wagner *et al.*, 2006.

Box 18.1 Toxicity evaluations of herbicides.

As has been the case with all pesticides, improvements in herbicides have led to the development of compounds that are not only more effective but also safer. Developments continue, but regardless whether one is concerned about target or non-target organisms, it is necessary to know some elementary toxicology. Much of the popular fear of "chemicals" ignores the simple fact that all substances are chemicals. Furthermore, all chemicals, natural or synthetic, can be poisonous to any organism if administered in a sufficient amount. The way to interpret matters involving toxicity is in terms of the kind of curve that depicts the basic relationship between dosage of compound and the biological response over the whole range of possible dosages (see Fig. 1). In the case shown in the figure, the dosage is that of some pesticide, and the response is the percentage of mortality in a series of a population of one species exposed to the various dosages; below a certain "threshold" or "no-response" level, there is no mortality at all. In fact, it is even possible that a compound might have beneficial effect at some dosage much below the threshold level. This would be called a medicine, whereas too much and it would be a poison.

The most important thing to note is that the dosage–response curve is asymptotic at both ends. This is because there is variation within the tested populations such that some individuals are much more resistant than others, although other factors can contribute to this kind of variance as well. The asymptotic nature of both ends gives two warnings. First, it is impractical, expensive, and environmentally unwise to seek 100% or even 98% mortality of target organisms. It is much better to be content with something like 90–95% and either tolerate the survivors or attack them by some other means. Second, it should be presumed that a curve of the same shape applies to humans and similar organisms, so its asymptotic nature near the no-response level is important. Biological variance, risk of accidents, and the possibility of hazards still unknown (such as the long-term cumulative and synergistic effects of multiple chemicals) are factors that are so important that maximum allowable dosage for these



Box 18.1 Figure 1 The typical form of a sigmoid curve by which the dosage of a biologically active substance is related to the response of a population of organisms. *Source:* Yale School of Forestry and Environmental Studies.

(*Continued*)

Box 18.1 (Continued)

organisms should be much less than the no-response level. For example, in the extreme case of human food, the legal 'tolerance" or maximum allowable amount of a given pesticide is 1% of the highest dosage at which no harm is observed in laboratory test animals.

It is also necessary to distinguish between **acute toxicity**, which involves single exposures and short-term effects, and **chronic toxicity**, which is associated with repeated exposures and long-term effects. Pesticide registration requires determination of both kinds. Recognition of chronic toxicity serves not only to guard against danger but also as a possible way of using pesticides more efficiently. Two or more applications at low dosages may kill more target organisms than a single high-dosage application. This is mostly because not all organisms are at the same stage of development and vulnerability. However, a non-target organism that is not damaged by one exposure may suffer from several. If the dosage–response curve of Fig. 1 is for acute toxicity, one for chronic toxicity with repeated exposures would lie far to the left and perhaps be steeper. The sigmoid curve form is useful for revealing the nature of the dosage–response relationship but cannot be plotted without substantial data for very high and very low dosages. Such curves can be converted to straight lines if the dosages are expressed logarithmically. This kind of statistical transformation enables dosages of the threshold and 99.9% response levels to be predicted with reliability from moderate amounts of data covering the range of responses.

The abbreviation LD50 denotes the dosage that kills 50% of the test organisms; it is the most important expression of the relative toxicity of different chemicals. It must of course refer to the organism used in the tests. Most tests rest on such inferences that trout react like minnows; alders, like beans; and people react like rats. The expression LC50 means "lethal concentration 50%" and might be used to denote the concentration of some substance in water that killed 50% of the minnows in it.

Another important toxicological consideration is the degree of persistence of a pesticide in the environment. The ideal pesticide would be the one that decomposed into such substances as water and carbon dioxide, and chloride ions, after it had done its work. Most modern pesticides break down in sunlight, water, and soil microorganisms. The best of them, in other words, are biodegradable. However, the breakdown within actual soil conditions is not well known and the formation of byproducts other than the major breakdown chemicals is likely.

Because life processes require water, pesticides should have enough affinity for water that living organisms can react with them chemically. DDT and other chlorinated hydrocarbon insecticides were banned because their insolubility in water caused them to be persistent. Their solubility in oils allowed them to accumulate in potentially active form in fats of animals and to be concentrated as they were passed along the food chain to eagles and other carnivores. The threatened extinction of these organisms through thinning egg shells served as an early warning symptom that harm might result from the long-term accumulation in people and other animals.

Although risks of non-target plants must be considered, herbicides are generally less dangerous to animals, including humans, than insecticides and rodenticides. This is because herbicides have been selected for toxicity to green plants, which have physiological processes quite different from those of insects and other animals. Potential dangers are likely to lie with additives, diluents, and contaminants (such as dioxin in 2,4,5-T) as in the herbicides themselves. It is prudent to regard any substance whether it is a pesticide, tree sap, or printing ink, as a possibly more hazardous substance than it is known to be.

Legal Aspects of Herbicide Use

In most countries, an herbicide cannot be marketed until a governmental regulatory agency has registered or approved it for a specified use. To get a compound registered, a company must show that tests have been reliably performed to demonstrate that it is both effective and safe enough to use. The label on an herbicide container is a document that has the force of law; it must be read and followed by the user. Among other things, it gives the chemical name and concentration of the compound, necessary precautions, allowable uses, and detailed instructions about dilution rates and methods of application. In most states and provinces, anyone who is going to use pesticides must pass examinations to demonstrate enough knowledge to get an applicator's license. The manuals that licensing agencies prepare to help users qualify are excellent sources of information about the necessary precautions. Only a few herbicides that are considered safe enough for general use are for sale to the public; these also have the same kinds of information for use and precautions on the labels (see Box 18.1).

Entry and Movement of Herbicides in Woody Plants

The many herbicides that are used to control herbaceous weeds in agriculture are sprayed directly on leaves or on the soil, to kill the plants on contact. Those herbicides are sometimes useful in forestry as well, but they do not solve the problem of controlling woody plants, which generally create the greatest problems in competing with

desirable species. It is necessary to get the herbicide inside the plant and get it to move to the critical area (usually the roots) to kill the plants.

The leaf and stem surfaces of land plants are almost always covered with waxes or other lipids (oily substances) that reduce water loss. These waxy materials in or on the bark are called **suberin** and on leaf surfaces they are called **cutin** (the entire leaf surface is called the **cuticle**). These coverings not only resist the absorption of water but they also tend to prevent water from sticking to the plant surfaces, causing the droplets to bead up into droplets and roll off. However, cutin consists of microscopic woolly strands of wax that are not a solid coating; molecules that are small enough can pass through the gaps between the strands. The structure and thickness of the wax varies tremendously among species. The same is true of the bark of woody plants. New shoots of woody plants are not waterproof, but after they have hardened and suberized, the bark becomes practically impermeable to water. The main pathway for water to enter a plant is, of course, through the roots.

Considering that these waterproof coverings exist, there are four ways that have been devised to get herbicides into woody plants. The first of these is the most obvious: (1) sprinkle herbicide pellets on the soil which dissolve with rain, or spray a water-soluble herbicide on the soil so that the plant will take it up into the roots. The second method relies on brute force: (2) cut through the bark of the stem, and inject a water-soluble herbicide into the cut. The final two ways are more complicated. They consist of using oil or a surfactant (a detergent-like liquid) to get the herbicide past the waxy cutin on leaves or the suberin on the bark. These include: (3) spray an oil-soluble herbicide on the stem. Because the oil does not wash off easily, it stays for a sufficient time so the herbicide can move through the suberin protection into the stem (this usually works only on small-diameter stems with thin bark). (4) Spray an herbicide that is mixed in oil or in a water-based surfactant onto the leaves of the plant; these materials allow the herbicide to move through the leaf cuticle into the interior of the leaf and down to the stems and roots.

Once inside the plant, the herbicides can move through water in the two vascular systems of woody plants: the xylem and the phloem. Herbicides that enter the plant through the roots or through cuts in the stems will be carried in the xylem stream up to the leaves. The xylem flow will only go upward, unless it is too cloudy or too hot and dry, when it will cease upward flow. These herbicides may kill the roots directly as they enter the fine roots, or will move up to the leaves and kill them. The other main herbicide pathway is through the phloem. When herbicides enter through the leaves, they are mixed with the sugars that are being produced through photosynthesis. The sugars and herbicides follow the source–sink pattern, moving from the source of sugars in high concentration in the leaves to the sink in the roots where sugars are being turned into cellulose.

Herbicide Compounds

The active ingredients of herbicide compounds have such complicated chemical names and structures that easier generic names have been devised for the convenience of users (see Tables 18.1 and 18.2). For example, N-(phosphonomethyl) glycine is called glyphosate. One of the trademark names is Roundup®, which has been applied to this herbicide and registered by the Monsanto Agricultural Products Company.

Each herbicide compound has a unique molecular structure, but most of them also have several possible modifications that affect the way they behave in their use. The active ingredient in most herbicides begins in the form of an **acid**. It is the acid part of the molecule that binds to the target site of the plant molecule. These acids can be dissolved in water, and they can be made even more water-soluble by changing the chemical composition into an **amine** salt. Another more important variation is to convert the same herbicide molecule into an **ester**. The ester form makes the molecule soluble in oil instead of water, and allows it to form an oily layer on the leaf cuticle and then the herbicide molecule can move through the cutin into the leaf. As soon as either of the amine or ester forms of the herbicide gets into the leaves, the plant enzymes shift them back into acid form, which is the active form to kill the plant. An additional variation is that some herbicides are water soluble and can be manufactured as **powders** or **granules**. This allows them to be spread on the ground and then they become active after they dissolve in rainwater.

Types of Herbicides

Phenoxy Herbicides (or Auxin Herbicides)

The first modern herbicides were phenoxy herbicides, which were developed for agricultural use in the 1940s. The oil-soluble ester form of the herbicide 2,4-D proved to be very useful as a broadcast foliar spray. This application selectively killed broad-leaved woody plants while not affecting conifers. It was soon found that 2,4,5-T was more effective in this use because it was slightly less toxic to plants. This meant that the herbicide could move into the leaf and through the phloem without killing those parts of the plant. That allowed the herbicide to travel through the living phloem and get to the root tissues which began to die as the herbicide concentration built up.

However, it was found that the manufacturing process for 2,4,5-T produced a contaminant (a dioxin compound which was carcinogenic). This made the compound unsafe to use, and it was deregistered in the United States in 1979. The dioxin contaminant does not develop in the other phenoxy herbicides, and these are still in use,

Table 18.1 Commonly used herbicides: common and trade names, modes of application, and circumstances of use.

Common name	Trade name	Manufacturer	Mode of application	Target/susceptible species
HERBICIDES REGISTERED FOR RELEASE FROM WOODY PLANT COMPETITION				
Glyphosate	Accord (Roundup)	Dow AgroSciences	Foliar: aerial and ground broadcast	Broad spectrum of hardwoods
Hexazinone	Pronone 25G/10G	Pro-Serve	Foliar: aerial and ground broadcast	Broad spectrum of hardwoods and white pine
Hexazinone	Power Pellets	Pro-Serve	Soil surface (hand-apply)	Broad spectrum of hardwoods
Hexazinone	Velpar L/ULW	DuPont	Aerial and ground broadcast or stem injection	
Imazapyr	Arsenal	BASF	Foliar: aerial and ground broadcast or backpack, soil and foliar active	Broad spectrum of hardwoods
Metsulfuron	Escort	DuPont	Foliar: aerial or ground broadcast or individual backpack	Black cherry, black locust, elm, dogwood, maple, and ash
Picloram	Tordon K	Dow AgroSciences	Stem injection/foliar: aerial and ground broadcast, stem injection. Apply after full foliar development and before summer heat	Broad spectrum of hardwoods and pines
Triclopyr (amine)	Garlon 3A	Dow AgroSciences	Aerial and ground broadcast, stem injection and stump treatment, best applied after full foliar development	Broad spectrum of hardwoods and pines
Triclopyr (ester)	Garlon 4	Dow AgroSciences	Basal-bark treatment and cut stump	Shrubs and severed stems of hardwoods
HERBICIDES REGISTERED FOR RELEASE FROM HERBACEOUS PLANT COMPETITION				
Atrazine	AAtrex Nine-0	Syngenta	Pre-emergence: will not control established weeds	Broad spectrum of annual grasses and forbs
Fluazifop-butyl	Fusillade	Syngenta	Foliar application: apply to grasses at the right time of development	Annual grasses and perennial grasses
Glyphosate	Accord	Dow AgroSciences	Foliar application, rainfall within 2–6 hours can reduce effectiveness	Broad spectrum of annual grasses and forbs and some perennials
Hexazinone	Pronone 5G	Pro-Serve	Soil active pre- and post-emergent, requires rainfall for activation	Broad spectrum of annual grasses and forbs and some perennials
Metasulfuron	Escort	DuPont	Soil active, early post-emergence application	Broad spectrum of annual grasses and forbs and some perennials
Sulfometuron methyl	Oust	DuPont	Soil active: immediately before or just after weed emergence	Broad spectrum of annual grasses and forbs and some perennials

Source: Adapted from Nelson and Cantrell, 2002.

including: triclopyr, picloram, 2,4-D, and 2,4-DP (diclorprop). These can be used as amine (water-soluble) or ester (oil-soluble) forms for chemical girdling, basal bark spraying, or foliage spraying.

Phenoxy herbicides act by deranging respiration, growth of tissues, and many other biochemical processes in plants. That is why they are called auxin herbicides; the plants grow themselves to death. Trade names include *Tordon*, *Access*, and *Garlon*.

The animal toxicity of the compounds themselves is low, and they are readily broken down by soil microorganisms. Picloram has the problem of leaching, and 2,4-D leaches in sandy soils, but triclopyr does not.

Phosphonalkyl Herbicides

The most important of the phosphonalkyl compounds is **glyphosate**, which has been the most widely used herbicide in forestry for several decades. It was discovered by

Table 18.2 Descriptions of the particulars for each herbicide that includes environmental concerns for **toxicity** and **volatility**.

Common name	Environmental concerns
Atrazine	A restricted-use pesticide. The product is not highly mobile in soils, and registers as a very low order of toxicity. Low volatility
Fluazifop-butyl	Product is not mobile in soil. Low oral toxicity but damages skin and burns eyes. Low volatility
Glyphosate	Absorbs tightly to soil particles. Very little leaching. Volatility negligible. Low toxicity to fish and wildlife. Short persistence
Hexazinone (Velpar)	Mobile in soil with a persistence half-life of up to 6 months. Volatility negligible. Toxicity low, but can cause severe eye irritation
Imazapyr	Fairly stable in soils and persistent. Negligible volatility. Low toxicity to fish and wildlife. Short persistence in soil
Metsulfuron	Negligible volatility. Low oral or dermal toxicity
Picloram	Restricted-use pesticide. Long-term persistence. Negligible volatility. Low toxicity to fish and wildlife. Breaks down rapidly in flowing water
Sulfometuron methyl	Fairly mobile in soil both downward and with surface runoff. Negligible volatility. Low oral and dermal toxicity
Triclopyr	Potentially mobile but readily broken down by microbes. Very low toxicity. Negligible volatility except for ester-based applications

Source: Adapted from Nelson and Cantrell, 2002.

a Monsanto chemist in 1970 and developed as an herbicide in the 1980s. It cannot be modified to an ester form to make it soluble in oil, so it is used dissolved in water. It can be taken up in water solution by leaves and twigs, especially when mixing it with a surfactant, which improves the penetration of the herbicide through the leaf cutin. It is readily translocated through both the phloem and xylem, so it can move to the roots and kill them. It is very toxic to woody plants, including conifers. Glyphosate is effective in the unselective foliage spraying methods used to prepare sites for planting. It can also be used as a foliage spray to selectively kill broad-leaved species to release conifers, but this depends on careful timing to apply the herbicide when both the broadleaves and the conifers are in specific growth stages. Glyphosate cannot be used in soil applications because it is tightly bound by soil; if it is sprayed on the soil, it will not move into the roots. This compound is very low in animal toxicity; it is biodegradable, being decomposed by microbes in the soil, and it is tightly bound to soil and organic matter, so it does not leach unless it is applied prior to a high rainfall event or to non-structured sandy soils where sorption is weak and water can pass through quickly (Veerecken, 2005; Borggaard and Gimsing, 2008).

Triazine Herbicides

This group of herbicides includes **atrazine** and **hexazinone**. They can be applied as a liquid (dissolved in water), as a powder or granules. They have the useful property of being toxic to grasses but not highly toxic to conifers.

Atrazine is rather immobile. It does not move into the plant or through the xylem or phloem, so only the plant tissues that come into contact with the herbicide are killed. For this reason, they are used as a pre-emergence herbicide in nurseries or on planting sites. The herbicide stays at the surface (usually spread as granules that dissolve when rain soaks them) and kills the emerging roots of germinating weeds. Atrazine does not have much effect on established weed plants. Hexazinone is a much more widely used triazine herbicide for silviculture. It is very soluble in water and is taken up by roots effectively enough that solutions of it can be sprayed at the bases of trees and shrubs to kill them; spray guns are used for this kind of application. Hexazinone can also be sprayed on the foliage at low dosages to release conifers from broadleaf species. The triazine herbicides disrupt photosynthesis and nitrogen metabolism. Trade names are *Aatrex* for atrazine and *Velpar* and *Pronone* for formulations of hexazinone. These herbicides can bind to organic matter and clay but have the potential to leach in sandy soils.

Imidazolinone Herbicides

A more recent addition to the herbicides used in forestry has been those belonging to the chemical family of imidazolinone, with the main compound being **imazapyr**. These compounds inhibit an enzyme that produces three amino acids that are critical for growth of meristem tissues. These herbicides are absorbed through both the roots and the foliage and translocated by xylem and phloem to the roots. The amino acids are depleted slowly, so the death of the plant roots is not rapid, but is effective. There is high soil residual activity, causing newly germinating weeds to die for months after the application. Conifers are quite tolerant of imazapyr, so timing the herbicide spraying with growth stages is not important. However, imazapyr is frequently combined with glyphosate, causing the timing of the combined mixture to become more important. The synergistic effect of this combination makes it possible to use extremely low application rates and still be effective.

Methods of Applying Herbicides

Stem Injection and Chemical Girdling

Stem injection and chemical girdling are used for killing trees that are larger than saplings. These techniques are too costly for use in stands where trees are small and numerous; the lower size limit is about 2 in (5 cm) in diameter. Any size of tree larger than that is acceptable. These methods are used in precommercial thinning and in release operations (for both cleaning and liberation treatments).

For large trees, incisions are cut in the bark, as is done for girdling a tree (as described earlier in this chapter). However, unlike girdling, where the cambium needs to be completely bisected around the circumference of the tree, only two to three incisions (sometimes only one) need to be made to pry open the bark and the wood. An herbicide is then dissolved in water and sprayed or injected into the cuts to kill the cambium and phloem. The cut goes into the wood, but that is done just to make sure that the phloem and cambium are cut. The purpose is to achieve a chemical girdling in which the cambium and phloem are killed in a ring around the stem. The sideways movement of herbicide as it moves up through the xylem may cause complete girdling higher in the stem. The herbicide will diffuse around the stem and it will complete the break in continuity of phloem and cambium around the stem. Water and nutrients will continue to move upward in the xylem and provide the leaves with water and nutrient, but sugars cannot move down the phloem, so the tree will gradually die. This gradual loss of carbohydrates may reduce the basal sprouting as the tree dies, but this varies greatly among species. This treatment can also be done with a hypo-hatchet, which is a hatchet with an herbicide injector built into the hatchet head, and connected to an herbicide container. Each stroke of the hatchet will inject herbicide into the stem cut. For smaller trees, an injector can be used to stab into the base of a tree and squirt herbicide like a large hypodermic needle. Two or more injections are given around the stem circumference to ensure that it is girdled internally.

Under some circumstances, downward movement can occur in the xylem after stem injection. If the herbicide can be applied almost simultaneously with the cutting, the breakage of the sap columns, which are normally under tension, can suddenly pull some of the herbicide downward. Solutions can also diffuse very slowly downward in the xylem at night or at other times when transpiration is not actively pulling water upward. In fact, problems can arise if trees are connected by intraspecific root grafts and one tree pulls the herbicide up from the roots of another. This phenomenon, called **flashback**, is most common when the herbicide has been injected into a small, overtopped tree and pulled into another by its large, actively transpiring crown. The best way of avoiding this effect is to make the injections higher on the stems and at times when transpiration is active, such as a sunny day. It is also a reason not to poison small, feeble trees in precommercial thinning; this is usually a time-consuming waste of effort.

Cut-Surface Treatment

The cut-surface (or stump-surface) method involves application of a water-soluble herbicide to the surface of freshly cut stumps. The only purpose of this treatment is to kill the roots in order to prevent sprouting. The herbicides really only need to be applied to rings around the cut surface that are as close to the cambium as possible; there are no tissues to be killed in the inner parts of the stump. All effects depend on the slow downward diffusion of the herbicide. Therefore, the application must be done within a few minutes after the cuts are made because downward movement will be blocked by air bubbles or the swift formation of wound gums and resins. Various attachments to brushsaws have been developed for this purpose, so that as the brushsaw cuts the stem, a nozzle on the saw sprays the herbicide on the stump immediately. A spray bottle works almost as well.

Certain tree species that are known to vigorously sprout, such as sitka alder, red alder, and trembling aspen, can be treated with the native fungal pathogen *Chondrostereum purpureum.* The fungus has been widely tested in the past 20 years and can be appropriate when applied in the late summer and early fall to cut surfaces or girdled trees (Harper *et al.*, 1999; Pitt *et al.*, 1999).

Basal-Bark Treatment

Woody plants can be girdled by applying oil solutions of herbicides in a continuous band on the bark at the ground-line around the base of the tree. The purpose is to kill both the aboveground plant and any basal buds from which sprouts might arise. Because of the difficulty of getting satisfactory penetration of herbicides into thick bark, basal treatment is limited to use on shrubs and young trees with thin bark; this method is used to control the smaller shrubs and trees that are too small for stem injection. Directions usually specify that the oil solutions be applied so that the entire circumference of the lower 6–12 in (15–30 cm) of stem surface are wetted to the point of runoff. This is to ensure that enough runs down over the buried root-collar surfaces to kill the buds beneath them. This treatment can also be used to prevent stumps from sprouting, if the bark is thin enough. In this case, the herbicide in oil is sprayed on the sides of stumps, as opposed to the cut-surface treatment that uses water-soluble herbicide on the surface of the stump.

Soil Application

There are two distinctly different uses of soil application treatments in silviculture. Both require the use of water-soluble form. For use in site preparation, there are two possibilities. If all plants have been removed through mechanical site preparation, then a pre-emergence herbicide is used to kill the newly germinating weed seeds on the site. Herbicides in powder or granular form are dropped onto the soil surface. No spraying equipment is needed because rain dissolves the herbicide pellet to make it become active. These herbicides (atrazine and related triazine compounds) stay on the soil surface, and as the weed seeds germinate, their roots come in contact with the herbicides and are killed. If plants are already on the site, then it is necessary to use a more mobile water-soluble herbicide that will be taken up by the roots. The herbicide is sprayed on the leaves and soil; some will be taken up through the leaves, but most will move into the soil and will be taken up by the roots and kill the plants.

The other use is for release operations where the desirable "target" trees are hampered by competing vegetation. Foliar sprayers cannot be used because the nozzles of the foliar sprayers produce a broad mist of herbicide over a large area of the plants, both the competing vegetation and the target trees. Backpack sprayers have a more focused aim. Usually, the herbicide is sprayed in a radius of 3 ft (1 m) around the tree, being careful to avoid spraying the target tree. Some workers put a light-weight plastic cone over the target tree for a few seconds while spraying the herbicides to make it easier to protect the target tree. Also, when small saplings or clumps of woody stems (with thin bark) are competing with the target tree, herbicide squirt guns are available to spray metered amounts of solution on the bases of these woody stems from a distance of 10 ft (3 m).

Foliage Application

The most important use of foliar spraying is for release operations that kill broadleaf woody species and herbaceous weeds, but leave conifers unaffected. It can also be used for site preparation, where the task is to remove unwanted vegetation before regeneration is established. The selective aspect is the most difficult. The great advantage of foliage spraying in general, and aerial spraying in particular, is that they enable quick, large-scale release operations. One hour of aerial spraying can accomplish as much as months of hand brushcutting, and prevent resprouting as well.

Foliage spraying is relatively uncomplicated if the purpose is to prepare sites for regeneration by killing all of the existing vegetation. The difficulties arise when the purpose is to kill a sufficient amount of understory vegetation without causing unacceptable harm to the desirable seedlings and saplings. Selective foliage spraying usually requires herbicides that are either in oil-soluble form or mixed with a surfactant. Herbicides can also be applied to the leaves in ways that enable them to be translocated to, and then kill, the vital tissues in the roots and stems of woody plants. The purpose of foliage spraying is to kill the roots; killing leaves is incidental, and the work may fail if they fall off before the herbicide moves out of them.

There are a number of things that allow this selectivity between hardwoods and conifers in release treatments. The first is **differential wetting**, which has been the most common source of selectivity in foliage spraying. Most important is the simple fact that spray droplets are much more likely to fall off narrow leaves of conifers than off the broad leaves of angiosperms. This is why foliage spraying is so commonly used to release conifers from overtopping hardwoods. The second is **phenological selectivity**, which relates to the timing of plant growth. This is possible if there are times when desirable species are less susceptible to damage than the competing vegetation. In the spring, angiosperms leaf out and the roots become much more active before conifers start to regrow. Conifers are still dormant and their buds have not opened. This is a good time for application. It may also work late in the growing season, if leaves of angiosperms have not dropped yet, but conifers are not active. In applying this knowledge, one must be guided more by the stages of plant development than by the calendar. The appropriate stage and time for treatment are not the same with all herbicides, species, or sites, so it is necessary to apply all information and experience available. Careful planning can lead to an adaptable spray schedule that moves from stand to stand as the spring progresses, especially if there are differences in elevation that affect growing-season timing. The third is **biochemical selectivity**, which can help in some cases but hurt in others. Some plant species have enzymatic systems that can inactivate a herbicide; ash and maple species seem to do this to several common herbicides and these species are thus resistant to them. Other herbicides appear to have a biochemical trait that gives resistance to conifers but not hardwoods.

Aerial Applications

Aerial spraying can be done only by highly skilled individuals who are both licensed pesticide applicators and licensed aviators, operating under detailed contracts. The work is usually performed under nearly calm conditions early in the morning. The size of spray droplets is critical. If they are too fine, they are apt to drift; if too coarse, the foliage may not be covered with adequate uniformity.

If spraying is done from above, the foliage is covered much more uniformly than when it is done from beside or beneath. Aerial application generally requires lower

volumes, higher concentrations, and smaller amounts of total active ingredients than ground application. However, there is less risk of drift beyond the target area with ground application. Because of this problem, fixed-wing aircraft are seldom used and are actually illegal for some chemicals. The work is usually done with helicopters because it is faster, cheaper, and requires far less herbicide than spraying with mist-blowers from the ground. It is very important to do the spraying quickly because application of many chemicals must be closely synchronized with the development of the vegetation, and the windows of time to spray are short.

The boundaries of areas to be treated must be clearly visible from the air; maps alone are insufficient. Prominent features such as roads, ridges, and edges of clearcut areas should be used as much as possible, but it is usually necessary to have other markers as well, such as flags. Dyes can be used in the chemical tank to make swaths more apparent, and global positioning systems are used to assist the pilots. The use of advanced technologies such as electronic guidance systems tied to GPS has greatly improved accuracy of application (Thompson and Pitt, 2003). It is so costly to move an aircraft to an aerial spraying project that operations are feasible only if at least 500 acres (200 ha) are to be treated at once. One helicopter treats about 60 acres (25 ha) in 1 hour. The individual treatment areas must be at least 5 acres (2 ha) but are generally larger.

Extensive studies, in Canada in particular, have been done investigating the effects of aerial applications of herbicide. In a review of the literature examining aerial application to release conifers from hardwood competition by Lautenschlager and Sullivan (2002), the results show that non-conifer vegetation is reduced for 2–5 years before recovering, but enough to allow conifers to dominate the future stand. They found no direct effect on the fungal community or on the general health of animals, and that plant species diversity may actually increase. In addition, studies on herbicide effects on soil-solution chemistry recorded that nitrate leaching increased over base levels after application by a maximum of 5% on well-drained soils with no change recorded on poorly drained soils, and effects, if any, disappeared within 3 years (Briggs *et al*., 2000).

Ground-Based Foliage Application

If spraying can be done from the ground, it can be aimed to a limited extent, and this gives the possibility of **selective placement** of herbicides that is not possible with aerial spraying. Large, light cones or cylinders that are easily movable make ideal temporary protective covers for seedlings that should be protected from the spray. If smaller areas must be treated, it is best to do the work from the ground. For very small areas, there are mist blowers that can be carried on the sprayer's back, but they can cover foliage to heights of only about 12 ft (4 m). More powerful equipment can be mounted on skidders or tractors to reach much greater heights. Spraying from the ground is especially effective as a means of controlling understory vegetation underneath stands of trees that might be damaged by foliage spraying, or where the helicopter would have to fly too high, such as in shelterwood and some seed-tree situations. Small spraying devices similar to those used in gardens can be used for small-scale operations.

Herbicides can also be applied to low vegetation with wick- or mop-like devices that are used to wipe the materials over the leaves. Most devices are handheld and are used to release individual seedlings. This kind of equipment, mounted on tractors, can be used to kill strips of grass or similar vegetation prior to planting or between rows of planted trees in plantations, orchards, or agroforestry systems. Placement of the herbicide can be very accurate, and there is no risk of drift, but the method cannot be used on tall plants.

Stem or Stem–Foliage Spraying

In foliage spraying, it is almost inevitable that the surfaces of small branches as well as those of leaves will be coated. If the herbicide is oil soluble, this can add significantly to the phytotoxic effect. In fact, it is sometimes advantageous to treat the stems of small deciduous trees when they are leafless. This kind of "dormant" spraying can, for example, be used in spring and fall to release Douglas-fir, hemlock, and spruce, from red alder and other angiosperms in the Pacific Northwest (Newton and Knight, 1981). The effectiveness of the treatment appears to depend on what amounts to a large-scale girdling of virtually all conductive tissues at the top of the plant as well as wholesale killing of dormant buds.

Better understanding can be obtained from Ashton and Crafts (1981), Newton and Knight (1981), Buchel (1983), Garner and Harvey (1984), and other sources such as the *Herbicide Handbook* issued by the Weed Science Society of America (Beste, 1983).

Use of Insecticides

It must continually be emphasized that insects and diseases are very much a part of a forest's cycle of death and renewal, and play an important part in the ecological processes of a forest's productivity and succession (Goheen and Hansen, 1993). However, there are major native pests of trees that have strong negative economic impacts on the management of forests. These are the root rots associated with Douglas-fir and its coniferous associates, the bark beetles of the southern and western hard pines, and the spruce budworm of the true firs and spruce. Their effects are more important than more

selective pests in other forests because they affect monodominant forest types where the death of one species has a major impact on the ecology and economics at a landscape scale. Their outbreaks have been tied to past land-use histories that have predisposed these forests to stresses, often from overstocking linked to fire protection, or from heavy cutting that has created large swaths of even-aged forest (Speight and Wainhouse, 1989).

The mixed-species hardwood forests have their diseases and insects, but because most of these pests are species or family specific, impacts to the forest type are not nearly as dramatic. What is more noticeable is the continued impacts of exotic invasives on forests, such as emerald ash-borer, Asian long-horned beetle, hemlock wooly adelgid, chestnut blight, gypsy moth, beech bark disease, and Dutch elm disease. These are all examples of human follies made by importing horticultural stock, or the pests themselves, by carelessness or in some instances on purpose.

In the 1950s, in an era of thinking that forests can be closely controlled by humans, the application of chemical insecticides for forestry was thought to be the best method of eliminating insect outbreaks. These insecticides were general, killing all insects that came in contact with the application. Chemical spraying to control for insect outbreaks using organosynthetic pesticides reached their zenith in the late 1960–1970s, with little to show in the way of long-term success (Speight and Wainhouse, 1989; Kogan, 1998), but to the huge detriment of the environment. In the past 30 years, more sophisticated approaches have been and continue to be developed under the name **integrated pest management (IPM)**. Its history can be traced all the way back to the late 1800s with the advent of ecology and our understanding of the interconnections between insects, plants, and disease (Kogan, 1998). The focus of IPM is the manipulation of push–pull strategies by creating a forest composition, an age-class distribution, and a structure that can act as an unattractive resource for a potential pest (push), while luring pests toward an attractive resource (pull) (Cook, Khan, and Pickett, 2006). Other strategies of IPM rely on the promotion of biological controls of pests by facilitating their predators and diseases to self-regulate their populations. The most obvious example is the use of *Bacillus thuringiensis*, which is now a widely commercially available bacterium that can control the larval stage of a wide number of defoliating insects (Cunningham and Frankenhuyzen, 1991). Much interest exists in developing natural plant chemicals as insecticides for specific types and kinds of insect pests (Helson, 1992; Kogan, 1998). IPM remains at the core of controlling pests and with the development of new monitoring and evaluation techniques. When an outbreak is detected the immediate implementation of IPM treatments can control the outbreak. Treatments include sanitation and salvage cuttings, the use of prescribed fire, soil-site treatments, and changing the species composition and age class of the affected forest. The best examples can be seen with the sophisticated IPM approaches taken with bark beetle outbreaks in the southern US for pine plantations (Waters, Stark, and Wood, 1985; Coulson *et al.*, 1989; Fettig *et al.*, 2007). Further details on forest health issues and silviculture can be found in Chapter 26.

Prescribed Burning

Fire can be used both constructively and destructively in managing stands and forests, similar to cutting. The practice of using regulated fires to reduce or eliminate the unincorporated organic matter of the forest floor or low, undesirable vegetation is called **prescribed burning** or **controlled burning**. The burning is conducted under such conditions that the size and intensity of the fires are no greater than necessary to achieve some clearly defined purpose of timber production, reduction of fire hazard, wildlife management, or improvement of grazing (Chandler *et al.*, 1983; Fahnestock, 1976).

Prescribed burning (which is the preferred term) has been coined to distinguish the use of fire as a silvicultural tool from its application for other uses. Very similar types of burning have been traditionally employed in many regions, especially in the southeastern US, to keep the forest open enough for grazing or other uses. For the purposes of this discussion, prescribed burning is regarded as involving fires that are set to burn through fuels that naturally occur on the forest floor, usually under existing stands. Thus, the burning of slash involves hotter fires and much heavier concentrations of fuel so that it is a kind of site-preparation treatment (see Chapter 7), rather than silvicultural prescribed burning.

Purposes and Effects of Prescribed Burning

The fact that a species is adapted to fire does not necessarily mean that fire has a practical, safe, and feasible place in its silviculture. Various cutting practices, herbicidal and mechanical treatments, or other kinds of disturbance can be used to simulate the effects of fire. However, it is the most common of the regenerative disturbances of natural forests, and its application is usually cheap; its silvicultural role needs more use and understanding than is typically dedicated. When properly done and in appropriate situations, burning accomplishes a number of beneficial things.

The most common objective of prescribed burning is still **fuel reduction**. In many respects, it is a more satisfactory method than conventional slash disposal because it eliminates most of the readily flammable fuels rather

than just the debris left from logging. However, it is important to note that prescribed burning makes forest areas only temporarily fireproof. Therefore, there is no substitute for a well-developed system of fire control.

The most important effect of prescribed burning in fuel reduction is the interruption of the horizontal and sometimes the vertical continuity (fire ladder) of flammable materials. The interruption of any vertical curtain of fuel is especially significant in the slash pine type of the southeastern US, the ponderosa pine type of the southwestern and Intermountain regions of the US, and the oak–pine type of southern New Jersey. Areas of slash or ponderosa pine types that have not been burned for a decade or more develop a tall understory of various flammable shrubs that become draped with fallen pine needles. In fuels of this kind, surface fires can rapidly develop into disastrous crown fires because there is a ready path for the flames to follow from the ground up into the crowns. In the oak–pine type of New Jersey, the presence of a shrubby understory tends to create the same dangerous condition. In each of these regions, successful silviculture depends heavily on the prevention of crown fires and it has been shown that prescribed burning is one of the only dependable means of forestalling them.

Prescribed burning can be effective in **preparation of seedbeds** for regeneration of wind-disseminated tree seed species, like the birches, poplars, and pines, which become established readily on bare mineral soil. Heavy-seeded species, such as maples and beech, do not become well-established in these soil conditions. This is beneficial in many cases because these species are not wanted within the vast areas where pines are the main focus species.

Prescribed burning is also a means of achieving **control of competing vegetation**. This often has the effect of slowing or stopping natural succession by killing the current understory regeneration. However, where the aim is to prevent invasion by hardwoods, as in stands of southern pines, burning must be done fairly often because only the seedlings are likely to be killed by fire; saplings will resprout, and larger trees may only be scarred. If soil moisture is a serious limiting factor, elimination of the understory may improve growth of the overstory substantially, such as for the ponderosa pine type (Sutherland, Covington, and Andariese, 1991). Increases of soil moisture (as much as 25%) have been observed (Zahner, 1955) on fine-textured soils in southern Arkansas, where the rainfall is much less than farther east.

Prescribed burning can kill roots of perennial grasses only where there are large amounts of fuel, such as fallen snags or large chunks of wood that ignite and burn for a long enough period to heat the soil below the surface (Weaver, 1951). Both in nature and in practice, surface fires must occur quite frequently if they are to be very effective in keeping brush and other understory vegetation in check. Fire is a rather cumbersome tool for accomplishing this purpose, and it is fortunate that it can now be supplemented or replaced by herbicides.

The most traditional use of fire in forests is for the **improvement of grazing** for livestock, and for stimulating herbaceous species and sprouts of woody plants for the **improvement of wildlife habitat**. These applications are discussed in Chapter 26. Burning can be employed in **recreation management** to maintain a park-like appearance in stands that would otherwise develop understory jungles. Large areas of southern pine forests, which now have understory tangles of shrubs, small trees, and briars, were more pleasant places in the era of frequent burning to promote grazing. As a byproduct, fires can probably be used more than they have been for reducing insects and forests' proneness to disease. The use of fire can sterilize the understory and create more desiccating conditions that are anathema to fungi and bacteria, although it aggravates problems with some when trees are injured. Most of the effects are subtle and indirect. One decisive role is in the direct control of the defoliating brown-spot fungus of longleaf pine, to be considered later. Burning also sometimes reduces problems with annosus root rot.

Prescribed burning has sometimes been successfully used to achieve the effects of **low thinning** in sapling stands of ponderosa and southern pines (Sutherland, Covington, and Andariese, 1991). The main purpose, particularly in the ponderosa pine type of the Intermountain west, is to restore forests back to more open stands that are less prone to severe wildfires. There is a growing amount of literature demonstrating the effectiveness of applying combinations of low thinning and prescribed burning to lower risk of severe wildfire, particularly in heterogeneous landscapes where treatments are strategically planned and in climates that are not exposed to extreme droughts (Biswell, 1999; Pollet and Omi, 2002; Fernandes and Botelho, 2003; Finney, McHugh, and Grenfell, 2005).

Potential Damage from Prescribed Burning

Fires started by incendiaries, accidents, or lightning cause so much damage to forests that it is not easy to reconcile prescribed burning with efforts to educate the public about fire prevention. Sometimes fire-prevention advertising exaggerates the effects of fire, and thus plants the seeds of future trouble (Pyne, Andrews, and Laven, 1996).

Prescribed burning has its greatest usefulness in the regions where difficulties with fire are the greatest, simply because valuable species that are naturally well-adapted to fire are most likely to occur there. In many respects,

the use of fire in slash disposal and prescribed burning is essential if risk of wildfire is to be reduced.

As already indicated, only exceptional kinds of soils are harmed by fire. Prescribed burning is useful mainly in forest types where natural fires are common (Covington and Sackett, 1992). If burning had any seriously harmful effects on the soils involved, they would probably already be ruined. Successful prescribed burning generally makes fires less severe than they were before the initiation of comprehensive programs of fire control and silvicultural management. The harmful effects of fire are much more likely to take the form of obvious and long-enduring effects on the vegetation than of subtle damage to the soil (Lutz, 1956). However, in some circumstances, fire has been used too frequently and soil-moisture conditions have been affected by reduced organic matter and changes in soil porosity (Boyer and Miller, 1994).

The effects of prescribed burning on standing timber depend on the size of the trees and the extent to which their stems and crowns are heated by fires. Because the primary source of fuel lies on the ground, the damaging effects ordinarily take the form of complete or partial heat-girdling at the ground line. In hotter fires, the effects extend farther up the trees, especially on the leeward sides of the stems where heated air accumulates. If there is a large amount of slow-burning dry fuel on the ground, there is risk that enough heat will be generated to support burning or overheating of the foliage. No North American species other than longleaf pine can withstand burning until rough, thickened bark has developed on the lower parts of the stems. The main portion of the crown canopy must also be well above the height of the flames.

The extent of injury to any part of the tree depends on whether the living tissues are heated above the lethal threshold of 130 °F (55 °C) and how long such a temperature is maintained. Therefore, any factor that hastens the transport of heated air out of the forest reduces the danger of damage. For this reason, it is better to conduct prescribed burning on level terrain when there is a gentle breeze rather than in calm weather. However, on pronounced slopes, sufficient updrafts develop to allow burning when there is no wind.

The initial temperature of the living tissues is also important in determining the highest temperature that they attain. The risk of injury is lowest when burning is done in the winter because it takes such a large amount of heat to raise the tissues to lethal temperatures. **Headfires**, which travel with the wind, are often less damaging than **backfires**, which burn against the wind, because the heat is carried upward more rapidly and high temperatures are not as long sustained close to the ground. However, headfires are more likely to spread to the crowns and should thus be avoided where the crowns are likely to be damaged.

Prescribed burning is applicable only in stands composed of trees that have reached fire-resistant size. It is not easily used in uneven-aged stands because it damages reproduction. The only way in which prescribed burning can be applied in uneven-aged stands is to have intervals between episodes of cutting and burning, no shorter than the time required for reproduction to appear and develop resistance to fire. The best way to avoid damage to the forest from prescribed burning is to conduct it under the right conditions according to carefully developed plans.

Methods of Prescribed Burning

Burning prescription is the term used by fire managers for the plan that defines the appropriate climatic conditions and burning methods desired for a stand. The customary prescription in conducting a prescribed burn is to isolate the area to be treated by means of plowed lines (fire breaks or fire lines) that expose the mineral soil and are wide enough to prevent the fire from spreading. Because the construction of these lines is costly, every reasonable advantage should be taken of pre-existing barriers such as roads and swamps. The whole operation should be carefully mapped out with special regard for the selected conditions of wind and weather under which the burning is to be conducted (US Forest Service, 1971). The fire lines should be plowed out in advance according to this plan, but not so early that they are covered over with fallen leaves before the burning is done. The area to be treated should be subdivided into units no larger than can be burned in a period of about 10 hours, although several units may be burned simultaneously. It is not wise to let a fire run for a longer period because of the possibility of unforeseen changes in wind and weather.

Weather forecasts and measurements of fire danger should be used to select times for burning that are both feasible and safe. The wind should be steady in direction and not erratic or too strong in speed. The moisture content of both fuel and soil is important not only for safety but also for determining whether the right intensity of burning will be secured. Fires that merely smolder are costly to apply and cause much air pollution. The burning is best planned and conducted by the same personnel involved in the control of wildfires. Much can be learned about the behavior of wildfires from prescribed burning. There should be enough personnel and fire equipment at hand to deal with any fires that escape.

The most common practice is to use backfires (Fig. 18.2). **Flanking fires** (**quartering fires**), which are set in lines parallel to the wind, spread more rapidly but are somewhat more likely to scorch the foliage of saplings or taller trees. Headfires can be used when the forest floor is too moist to be burned by backfires, thus increasing the number of days when treatment can be

Figure 18.2 Prescribed fire backing into the wind through needle litter and saw palmetto beneath a flatwoods stand of slash pine. *Source:* US Forest Service.

conducted. They are in some respects safer than backfires because they are more likely to go out than to escape from control if the wind shifts unexpectedly. The heat from them is carried away rapidly so that they are less likely to overheat crowns or produce fire scars on the stems of trees than are backfires. If headfires can be used safely, they are cheaper than backfires because they can cover an area much more rapidly.

The cost of prescribed burning depends on the size and shape of the units burned, the inflammability of the fuels, the length of fire line needed, the size of the crew, and the shape of the terrain. If the units are more than 25 acres (10 ha), the costs are usually very low. The cost of fire lines is the chief variable. High cost may result if there is a heavy accumulation of fuel requiring a series of small fires, or if there is so little fuel that the fires have to be relighted often. The costs of burning small tracts, areas with irregular boundaries, or narrow strips are rather high. However, if large areas can be treated in single operations, several burnings can be done for the cost of one broadcast spraying with herbicides. If the undesirable vegetation is small, such a series of burns may be almost as effective in controlling the vegetation and also can substantially reduce the amount of fuel.

Application of Prescribed Burning

The details of prescribed burning vary according to the species and objectives of treatment, the most important variable being the schedule of burning. Longleaf pine is one important species that is ecologically almost totally dependent on frequent surface fires (Grelen, 1983). The seedlings germinate in late fall and thrive best beneath the first year's growth of grass developing after a previous winter burn. Until they form the first dormant terminal bud about 9 months later, they can be killed by fire. They stay in the peculiar grass stage without growing in height, until the large tap-root grows to about 1 in (2.5 cm) in diameter. A sudden spurt of height growth follows with a brief period of moderate vulnerability to fire. During the grass stage, it is necessary to burn about every 3 years to keep the brown-spot disease in check. The spores that spread this disease can move by rain splash. Once the seedlings have become more than 3 ft (1 m) tall, frequent burning remains desirable, but the benefits become the same as with the other southern pines.

The most common purposes of prescribed burning under stands of southern pines are fuel reduction and the control of understory hardwoods that continually threaten to take over the stands (Fig. 18.3). The southeastern region has many dry soils on which hardwoods grow fast during the juvenile stages and tend to overwhelm conifers that only later show their superior adaptation to such soils. Fire has essentially the same role in the ponderosa pine forests of the interior–west as it does in the southern pines. On the best sites, fire prevents invasion by the relatively tolerant and less valuable Douglas-fir and true firs. Light surface fires also improve forage production and reduce the danger of serious fires.

(a)

(b)

Figure 18.3 **(a)** An untreated 45-year-old stand of loblolly pine with a dense hardwood understory at the Santee Experimental Forest on the South Carolina coastal plain. **(b)** Photograph taken on the same spot 6 years later, just after the second of two partial cuttings and after four prescribed burning operations. *Source:* **(a, b)** US Forest Service.

It may take rather frequent fires to keep hardwoods under control because only the seedlings are killed outright. Saplings usually resprout and can thus be killed back only to the ground. Larger trees have to be killed with herbicides or by girdling or cutting. One common sequence for eliminating degraded hardwood stands is (1) burning, (2) spraying of the resulting succulent sprouts, and (3) killing the large survivors through herbicide injection.

If large amounts of fuel have accumulated from long periods without fire, it may take several light winter fires to skim off enough successive layers to make it safe enough for fires that really favor regeneration. The fires that foster regeneration are often summer fires capable of exposing some mineral soil and killing small hardwoods (Fig. 18.4). Summer fires involve no risk of destroying any seeds that have fallen. Fires can be of many combinations of timing and intensity; the choice of these can be a fine art.

Prescribed burning plays a very crucial role in prevention of crown fires in the pine forests of the south and the interior western US, and the pitch pine barrens of southern New York and New Jersey. Although pitch pines can recover from crown fires by sprouting along the charred stems and branches, this greatly impairs the form of further growth of the trees. Crown fires in slash pine and most other tree species are lethal to trees and are highly dangerous.

Fires burning beneath natural stands also had an important effect on the maintenance of sugar pine and ponderosa pine, as well as the giant sequoia, in the mixed-conifer forests of the Sierra Nevada (Kilgore and Taylor, 1979). These forests are as difficult to regenerate as they are magnificent. The situation is complicated by shrub species that are also favored by fire and by heavy fuel accumulations from decades of fire exclusion. In ponderosa pine forests of the southwestern US, the post-thinning treatments in which the slash and needles were raked away from the base of the remaining trees, and the scattered slash was compressed to the ground with a D-6 bulldozer, reduced the prescribed burning mortality to less than 3% (Fulé, Jerman, and Gould, 2004)

Many of the better forests of moist, cool, northern climates, especially the birch and coniferous types, owe their origin to the effects of fire (Zasada *et al.*, 1977; Bergeron *et al.*, 2002). However, most of the fires involved were of the catastrophic kind that occurred at long intervals rather than light, frequent ones (Frelich and Lorimer, 1991). Therefore, the desirable effects of fire are normally achieved by broadcast burning of slash rather than by burning under the stands. One characteristic that virtually all Australian eucalypts have in common is adaptation to fire (Hillis and Brown, 1978). In fact, Australian sites that are too moist for fires seldom have eucalypts. Exposure of bare mineral soil from fire favors regeneration of this small-seeded genus. Many of the species sprout after crown fires, and some can even renew their crowns by sprouting after crown fires. Many of the so-called ash group, usually of the

Figure 18.4 A stand in the same place and treated similarly to that shown in Figure 18.3 but after an additional 5 years, with dense natural reproduction of pine replacing the original hardwood understory. The treatment here consisted of one winter fire followed by three successive annual summer burnings. *Source:* US Forest Service.

moister sites, are adapted to regenerate after catastrophic fires, best simulated by true clearcutting and slash burning. However, in some forests of drier sites, prescribed burning is often conducted beneath the stands for fuel reduction and other purposes, as described in connection with the southern pines.

There is a significant pattern in the application of prescribed burning in those localities where it is used. When management is started in a forest type that owes its characteristics to repeated burning, it is logical to attempt to conduct silviculture by methods that simulate some of the important effects of fire, but do not actually include prescribed burning. If this line of action produces a satisfactory result, there is no reason to use fire, which can be a treacherous tool.

Currently, the exclusion of fire has created circumstances in which the problems have multiplied progressively. The essential conditions for reproduction of the desirable trees have been less frequently created, and the understory tree and shrub species of little value have adapted to the new conditions. As fuels accumulated, wildfires that formerly caused little damage have an increasing tendency to develop into conflagrations; often this development proceeded more rapidly than fire control could be improved to meet it. Frequently, the point has been reached where undesirable, sprouting vegetation can no longer be eliminated by fire and has had to be left or attacked by more laborious methods. For example, overzealous control of fire in certain places of western North America has promoted encroachment of more mesic species prone to root rots and other diseases. This has led to cataclysmic fires that rarely occurred previously on these sites (Sampson and Adams, 1994). What is also important to recognize is that, although fire suppression has been widespread across the western US, the range of climates and forest types mandate a variety of ways of restoring forest structure, reducing fuels, and reintroducing fire back onto the landscape (Schoennagel, Veblen, and Romme, 2004; Stephens *et al.*, 2012).

In other kinds of American forests, most silvicultural use of fire, except for slash disposal, is still in an experimental stage. In the northeastern US, Native American populations burned in the understories of hardwood forests to promote forbs and grasses to improve hunting of wildlife (Day, 1953; Abrams, 1992). Agricultural development then spread across the region and involved the use of fire for grazing improvement. This may have promoted the development of stands dominated by oak and hickory because of the ability of oak and hickory to re-sprout after fire. Although fire has not yet been used in most silviculture in this region, it is being tested mostly to favor oak regeneration by top-killing all shrub and tree regeneration, and then having oaks sprout rapidly. Results have been variable so far, with successes reported when stands burned once, with an open overstory (Ducey, Moser, and Ashton, 1996), and when the groundstory was repeatedly burned at periodic intervals (Niering, Goodwin, and Taylor, 1970; Nyland, Abrahamson, and Adams, 1982).

Slash Pile Burning

Slash pile burning is a major component of thinning treatments in western conifer forests. Prescriptions called “fire hazard reduction” and “fuels reduction” usually require slash to be piled and burned, particularly if it cannot be chipped or there is no pulpwood market (Finkral and Evans, 2008) (see Chapter 7 for more details).

Use of Fertilizer

Applying fertilizer to forests that originate from natural regeneration is rarely done. Most native forests are now restricted to marginal lands that are difficult to work because they are prone to flooding or droughts, or they are on steep, rocky, or infertile soils that are difficult to access with machinery. However, plantations, orchards, and trees planted in urban environments commonly have fertilizer applied. For street trees, nitrogen fertilization can be commonly applied at the time of planting and at periodic intervals over the trees’ growth on poor soils (Struve, 2002). The most appropriate time to apply fertilizer is as a surface application during the early growing season. Fertilizer applied to nutrient-rich soils is inconsequential, mostly because other vegetation acquires the fertilizer and not the target tree (Struve, 2002). In orchards, application of fertilizers is most successful when competing herbaceous groundstories are kept in check (Dasburg, 1987). Orchard systems are commonly kept bare around the planted stems by application of herbicide, with live mulches mowed in between rows. Fertilizers are often applied in solution with irrigation (called **fertigation**) at the beginning of the growing season, and then periodically over the course of the season until fruit maturation (Kipp, 1992).

Conifer plantations for commercial production of timbers such as Douglas-fir in the west, loblolly pine in the south, and white spruce in the boreal north, are usually supplemented with fertilizers. Miller (1981) summarized the use and rationale for fertilization with three important points. The first is that the application of fertilizer is to benefit the trees, but does not measurably change or improve inherent site productivity unless it is a large input as compared to the total amount of soil capital. The second is that without actual site improvement, fertilizer can be thought of as accelerating tree growth to a given size in a shorter time, thus reducing rotation age. During the initiation phase of stand development before

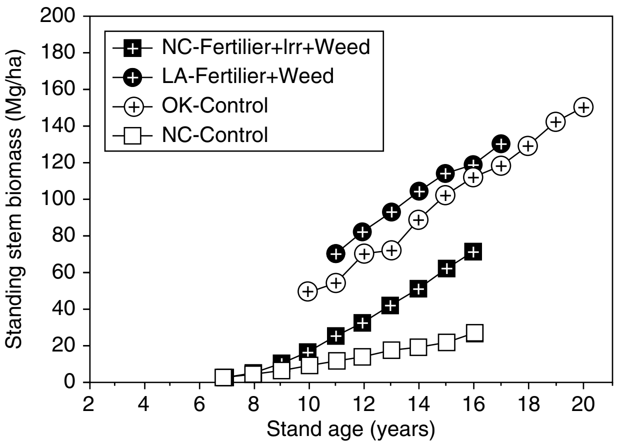


Figure 18.5 Stemwood biomass accumulation for unthinned loblolly pine plantations subjected to fertilizer, weed control, and their combinations as compared to controls at different sites across the US South. *Source:* Jokela *et al*., 2004. Reproduced with permission from Elsevier.

canopy closure, trees can be expected to respond favorably to fertilizer application. Beyond canopy closure, in the stem-exclusion phase, trees are much more responsive to fertilizer application after thinnings, when crowns are free to grow. The third point is that on nitrogen-poor sites, its immobilization in biomass and organic matter can lead to deficiencies, but this declines with decreasing demands, as trees age.

In the southern US, Jokela, Dougherty, and Martin (2004) synthesized research on long-term trials of fertilizer applications, understory control and thinning, and their combinations, on intensively managed loblolly pine plantations. They concluded the single most important driver of productivity was soil nutrient availability. All sites that received fertilizer and weed control responded in growth from 2 to 3.5 times that of plantations that had not had these treatments (Fig. 18.5). Southern pine plantations are therefore commonly fertilized (Fox *et al.*, 2007). Nitrogen and phosphorus are the nutrients most commonly applied. Phosphorus is applied on old, highly weathered clay soils (ultisols) at the time of planting in the amount of about 25–50 lb/acre (11–22 kg/0.4 ha). On most other soils in the southeastern US, nitrogen is also deficient and requires application at a rate of 200 lb/acre (90 kg/0.4 ha) along with phosphorus for best growth results. Fertilization increases leaf area which increases light capture, with average growth responses of about 55 ft^3/acre/yr (1.6 tn/acre/yr). Understories are noticeably darker and lack the diversity of herbs, shrubs, and grasses found within unfertilized plots. Earlier studies with Douglas-fir in the Pacific Northwest (Brix, 1981, 1983) revealed similar patterns, particularly coupled with thinning, where applications of nitrogen fertilizer increased stemwood biomass by about 25%. Fertilization noticeably decreased the diversity of the forest's understory, primarily because of the higher allocation in Douglas-fir to leaf area and increased shading (Thomas *et al.*, 1999).

Irrigation

Irrigation is used only in specific places for forestry purposes. The two most obvious purposes are for intensively managed biomass plantations planted on fertile but dry soils, such as in the dry interiors of Washington, Oregon, and California. It is also used for reforestation and agroforestry schemes for community development in developing nations such as the countries around the Sahel, the Middle East, parts of interior China, and west Asia where water is a limiting growth factor (Qureshi and Barrett-Lennard, 1998). On all of these lands, salinization can be a problem, leading to the toxic accumulation of salts at the soil surface.

Intensively managed tree plantations have often used a narrow set of fast-growing species such as cottonwood, eucalyptus, and sycamore. Production can increase dramatically, particularly with fertigation (irrigation plus fertilization) (Coyle and Coleman, 2005).

In the 1980–1990s, studies investigated the application of human and animal effluent as a fertilizer on tree plantations in Europe, North America, and Australia (Stewart *et al.*, 1990; Myers *et al.*, 1996; Smith, Hopmans, and Cook, 1996). Species can grow rapidly but worries about accumulation of metals in toxic amounts appear to have dampened the enthusiasm for this treatment.

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19

Pruning Methods and Applications

Introduction

In nearly all tree species, branches play an important role in forming the woody structure of the tree crown. However, branches also present a problem in silviculture, particularly when high-quality timber is the objective of management. As the main stem of a tree grows in diameter, the branches become buried in the stem. These branches that are encased in stem wood are called **knots**, and they are the most common defects of wood that is grown for timber products. In some situations, pruning these branches can be an important silvicultural practice for producing **clearwood** (that is, knot-free wood). In the past, old-growth trees were readily available for harvest, with a large outer shell of clear wood in their stems (the branches had died and broken off long ago.) This is no longer the case; old-growth trees are now scarce for harvesting. The use of pruning to confine the knots to a small core in the center of the stem can greatly increase the timber value of a tree. This is the main goal of pruning in commercial forestry, and it will be the main focus of this chapter. However, another important use of pruning is for the control of the white pine blister rust, which attacks nearly all of the white pine species. This will be described as well.

Pruning can also be used for other objectives that include: (1) the maintenance and care of urban trees within streets and parks; and 2) the techniques used in orchards and agroforestry systems to improve the form and yields of trees that produce fruits, nuts, and leaves. The techniques of pruning for these values are fundamentally different in that the pruning done for street and parkland trees is to affect the form of the tree. Pruning in agroforestry and orchard systems is to both create and maintain the form of the tree as well as to ensure reallocation to and from the reproductive and vegetative parts of the plant to increase yield.

This chapter is divided into three parts. In the first part, the ecology of natural pruning processes within trees is described. The second part includes the application of this knowledge to pruning trees in order to improve timber quality of closed canopy forests and plantations. The third part concerns the application of pruning techniques for open-grown trees within urban and agricultural lands.

The Ecology of Natural Pruning Processes

Growth and Structure of Branches

The development of branches and knots can be confusing, so it is worthwhile to review the life history of a branch. A main branch begins as a lateral bud on the top shoot of the main stem of a tree. One year later, the bud expands and produces a new lateral shoot (Fig. 19.1). This small branch then continues to grow in length each year and also begins to produce annual rings of wood. The growth of each annual layer of wood starts just below the newest growth of the branch and progresses down toward the main stem. The main stem of the tree is also producing its own annual ring of wood, which progresses from the top of the tree downward. The xylem, phloem, and cambium of each new layer of branch wood intermingles with the matching tissue types of the stem wood. The upper half of the branch is not directly connected physiologically to the stem, but the lower half is (Fig. 19.1). This connection in the lower half is vital because it creates a pathway for water and nutrients to reach the foliage of the branch through the xylem, and for carbohydrates and other substances to be translocated between the branch and the rest of the tree through the phloem. This pattern of growth continues for as long as the branch is alive.

The branch grows larger in diameter with each annual ring of wood laid down, and as the stem also grows larger in diameter, the base of the live branch continues to be buried by the stem diameter growth. If the branch dies, the stem wood no longer has any physiological connection with the branch wood. From that time on, the annual layer of stem wood grows around the dead branch as it would around a nail that had been driven into the stem, and the dead branch becomes encased within the live

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

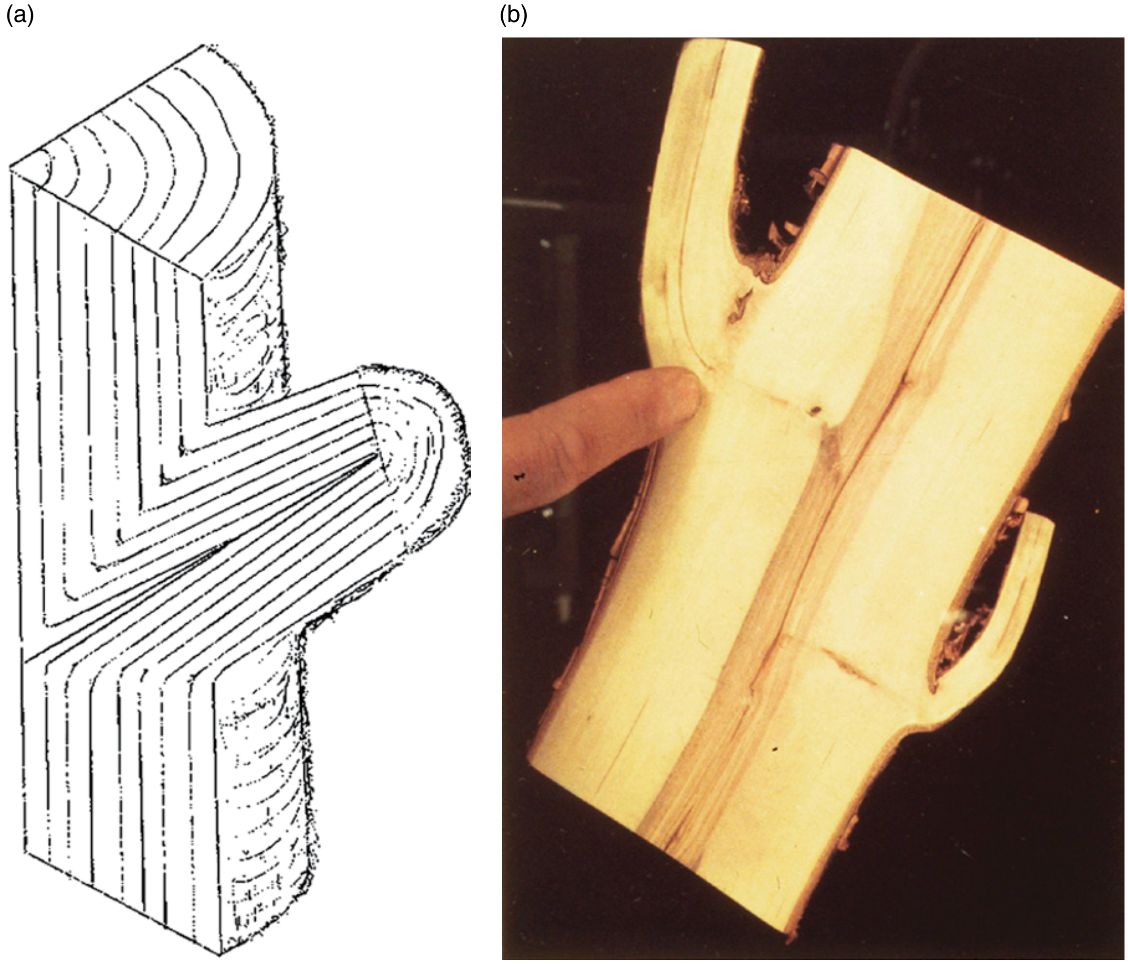


Figure 19.1 **(a)** An illustration of the annual growth over time since initial bud release to form a side branch on the main stem. Each linear segment represents an annual growth ring of xylem. In temperate–wet and boreal climates, the xylem laid down in the spring is called earlywood. This progresses into latewood that is laid down in the summer. The earlywood is often lighter in color and has larger conduits with thinner cell walls to move water up the tree faster than the darker colored latewood. In the section shown, the branch originated and developed at the same time as the main stem of the tree developed and grew out. *Source:* Yale School of Forestry and Environmental Studies. **(b)** A photographic section of a dormant bud that was released to form an epicormic branch at a later time than the actual formation and development of the main stem. The finger points to when the bud was released to form the epicormic branch. The actual bud trace can be seen all the way through the stem's annual ring growth, back to the pith. The bud remained connected to the stemwood xylem ever since its initial development at the time when the stem had just attained this height. In this case, the growth rings are hard to detect but the darker color depicts the older "heartwood" and the light color is the "sapwood". *Source:* US Forest Service.

stem. Eventually the stem will get large enough to grow over the stub of the dead branch.

With many species, as the tree produces layers of wood along the stem, it also forms a thickening of wood around each branch. This is called the **branch collar**, and it provides mechanical support around the base of the branch. A ridge of bark also develops along the upper half of the branch and the stem junction, where the wood does not make a physiological connection. This is called the **branch bark ridge** (Fig. 19.2).

Natural Pruning

In unmanaged forest stands, most branches die from lack of light, as a result of shading by branches of adjacent trees. The onset of this **natural pruning** or **self-pruning** process occurs at the time of canopy closure. The survival of a branch is dependent on its balance of photosynthesis and respiration. If light captured by the branch foliage cannot provide enough carbohydrates to meet the respiration needs of the branch, it will die. The more vigorous branches higher in the tree will not provide carbohydrates to help it survive. Fungi will then invade the dead branch and decompose the woody tissues. The surrounding living tissues and structures will **compartmentalize** the dead branch at its base. The branch weakens and eventually breaks off through the action of snow, ice, wind, and falling branches from above.

Self-pruning can occur in other ways as well. For example, water stress can cause the outermost branches

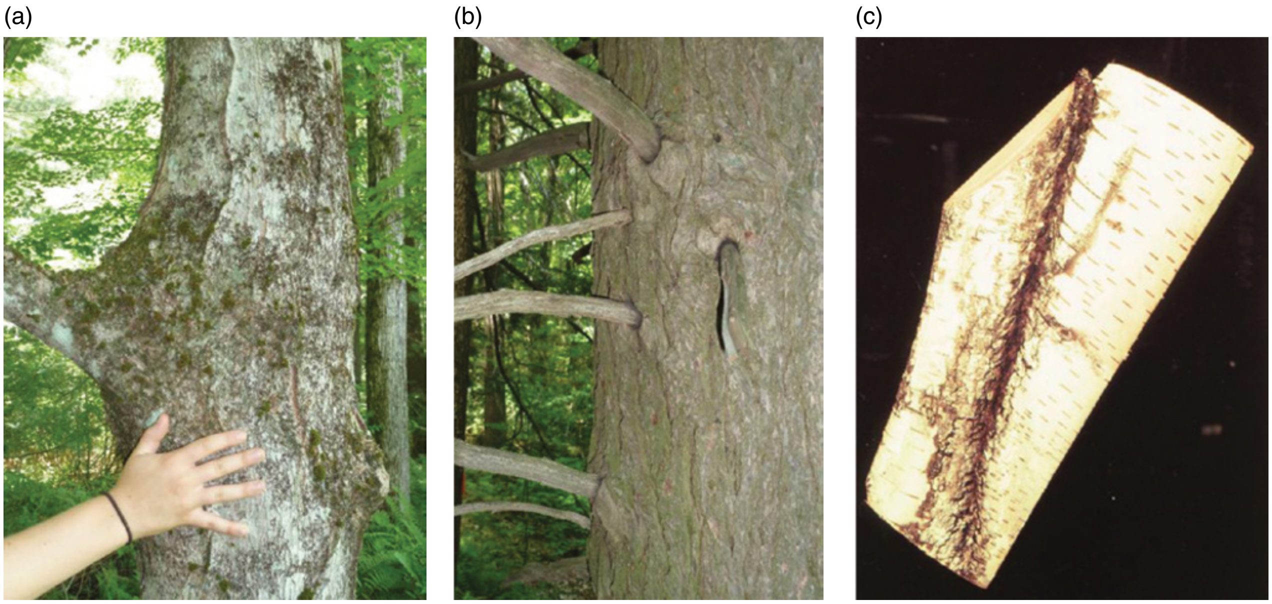


Figure 19.2 Species have very different branching morphologies that need to be recognized in pruning a tree. **(a)** A sugar maple tree with a very visible branch collar (swelling) around the limb. *Source:* Mark S. Ashton. **(b)** Dead branches of hemlock clearly being sealed off by the living bole wood. *Source*: Mark S. Ashton. **(c)** A birch with a branch bark ridge but no visible branch collar. *Source:* US Forest Service.

Figure 19.3 An illustration of crown shyness in *Dryobalanops aromatica* (Dipterocarpaceae), a rainforest canopy tree in Southeast Asia. *Source:* Mark S. Ashton.

of trees to die back. The extremities of plant parts are the most sensitive to stressors from many kinds of climate factors, such as desiccating winds, droughts, and heat injury. **Crown shyness** is another example of self-pruning of the finer twigs between and within canopy tree crowns, caused by periodic or continuous branch abrasion from wind (Fig. 19.3).

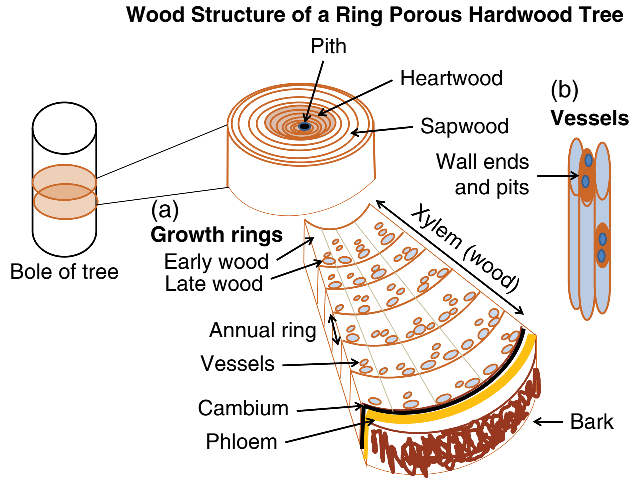
The branches of some tree species contain chemicals that make them resistant to decomposition, even after they have died. The most resistant are the spruces and white pines because of their resins and low nutrient concentration. The wood of most other conifers and nearly all hardwood species have higher nutrient concentrations, so their branches provide better substrate for fungi, and they are decomposed more rapidly. However, the resistance of branches to decomposition varies greatly among tree species. Most of these fungi do not feed on living sapwood tissue, so they don't move into the living tree stem after they break down the dead branch material.

The final step in natural pruning is the covering by new wood growth of the short stub left after the dead branch

has broken off. This process is called **occlusion**. The stem produces **resin** (also called **pitch**) in conifers, or **gum** in hardwoods. These flow over the branch stub and act as a barrier to microbial infection. **Callus tissue**, comprising unorganized cells, often develops after injury to the cambium and can produce a woody layer over the stub. Callus is a kind of meristem which can differentiate into various kinds of cells. The callus wood forms (or after injury reforms) the cambium layer which produces cells that differentiate into **xylem** and **phloem**. Xylem cells are layered inward annually by the cambium and comprise the wood that is responsible for transporting the vast amount of water to the leaves. This xylem wood is called the **sapwood**. In later years, this xylem wood seals and lignifies, and becomes part of the inner core as the functional xylem continues to be laid down from the outside. The non-functional inner xylem is called the **heartwood**. The phloem comprises the living cells that actively translocate the sugars and nutrients up and down the tree from leaves to roots and back, depending upon their use allocation.

In particular, this cambial process of xylem cell development allows the stem wood to produce layers of wood over the branch wound, making the occlusion of the branch complete. Faster-growing trees cover the wound more quickly, and the occlusion progresses more quickly with branch stubs that are shorter or smaller in diameter. The new wood that covers the old branch stub is the most dependable seal for excluding water, oxygen, and fungal spores from the interior of the stem. Even if decay has already started beneath a dead branch stub, it may cease to spread when water and oxygen are excluded by the covering of stem wood.

There are several other structures and chemicals that prevent or slow infections within wood, apart from resins and the occlusion of callus tissue. These include the orientation and density of the xylem walls. The denser, smaller xylem wood cells that are laid down during slower periods of growth in summer or at a drier period of the growing season can impede infection inward. Some trees lay down bands of cells called **ray parenchyma** as tangential layers between the annual rings of xylem. Their chief function is storage of carbohydrates but they can act to impede infections from going around the stem. All xylem wood has differing degrees of perforation at the cell ends to allow sap to move upward, but that can also serve to impede infection. The xylem cells in angiosperms are called **vessels**, while in gymnosperms they are called **tracheids**. Finally, there are chemical anti-fungal compounds in the sap of many species of trees. The complete process of sealing off infections chemically, by resins, through occlusion of callus and stemwood growth, and from the cell wall structures and densities of ray parenchyma, has been termed **compartmentalization** (Shigo, 1984a) (Fig. 19.4). The stub is therefore encased by this process and can be used in



(c)

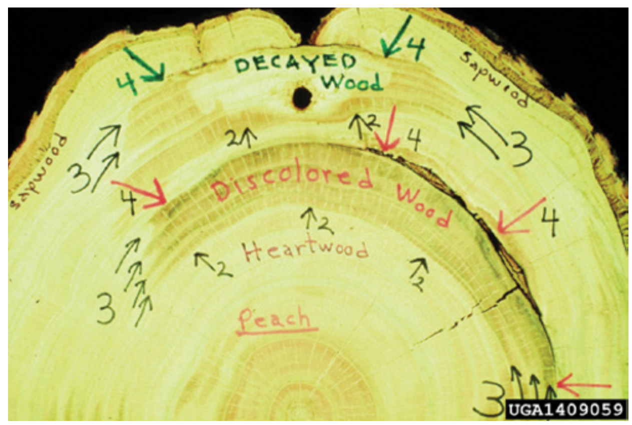


Figure 19.4 **(a)** An illustration of the wood structure of a tree at three different scales. At the large scale is the bole of a tree; within which, at an intermediate scale, is a cross-section depicting exterior younger wood (sapwood), interior wood (heartwood) and the pith. At the smallest scale the growth rings of xylem wood (heartwood and sapwood) are illustrated with the major zones of cellular wood anatomy (bark, phloem, cambium, and the vessels that make up the early and late xylem wood of a growth ring). The rings themselves act to prevent infection getting into the interior of the tree by growing denser smaller vessels (angiosperms) or tracheids (gymnosperms) later in the growing season (late xylem wood) and/or by developing a layer of different cells at the end that terminates further growth and concludes the growing season (e.g. rays). *Source:* Mark S. Ashton. **(b)** An illustration at a finer resolution of the vessels within the xylem. In addition plates (wall ends) between vessels serve to impede movement of infection up and down the tree. *Source:* Mark S. Ashton. **(c)** An example of compartmentalization of an infection in peach wood: callus tissue is growing around wounds at several places within the wood (depicted by arrows labeled 4); the cell wall structure of the vessels in the sapwood is preventing infection movement to the sides (depicted by arrows labeled 3); and the lignified vessels of the heartwood are preventing infection inward (depicted by arrows labeled 2).
Source: US Forest Service.

dendrochronology (the study of tree wood growth) to infer the historical growth of the tree.

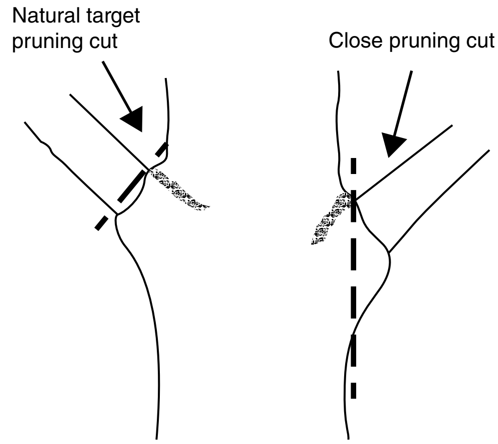
Pruning Trees to Improve Timber Quality in Forests

Pruning Techniques

Artificial pruning speeds up the process of the natural loss of branches. The technique of pruning branches may seem obvious, consisting simply of cutting branches off of the main tree stem. However, there are two ideas about where the cut should be made (Figure 19.5). One method (**natural target pruning**) consists of cutting the branch at the outer edge of the branch collar (the edge of the collar being the "targets"). The other method (**close pruning**) consists of cutting into the branch collar parallel to the main stem but not quite flush to the stem. The natural target pruning method avoids cutting into the branch collar, so it creates a smaller wound area. However, the diameter of the stem that contains knots (called the **knotty core**) will be larger with this method because the branch stub protrudes out farther from the main stem to the end of the branch collar. This is not the case with close pruning, because the branch stub is cut nearly flush with the stem, but the wound is larger in area because the branch collar has been cut off along with the branch.

It would seem that there is a tradeoff between maximizing tree health (making a smaller wound with natural target pruning), or maximizing clear wood production (making a shorter branch stub with close pruning). The natural target method was promoted by Shigo (1984a) and is widely used by arborists. The common use of this method in arboriculture has led to its adoption by some foresters for silvicultural purposes. However, many decades of research on silvicultural pruning on conifers have shown that close pruning is generally the better method in terms of both tree health and clear wood production (O'Hara, 2007). Creating a larger wound by cutting into the branch collar does not appear to cause increased fungal infection or decay problems. Rather, cutting into the branch collar stimulates higher resin production and callus wood growth that spreads over the wound, thus speeding up the occlusion process (Langstrom and Hellquist, 1991). The process is slower for dead branches than for live ones, but even with dead branches the branch collar should be cut in order to stimulate a faster occlusion process. Thus, the close pruning method generally produces both a shorter branch stub and faster healing of the pruning wound. This pruning approach is recommended for conifers. Hardwoods should conform to the natural pruning approach given the lack of research on close pruning (Kerr and Morgan, 2006).

(a)



(b)

Figure 19.5 **(a)** An illustration of the two pruning techniques on similar branches. Left, the *natural target pruning* method cuts the branch at the outside edge of the branch collar. Right, the *close pruning* method cuts through the branch collar, parallel but not quite flush to the stem. The close pruning method is favored for silvicultural pruning for timber production in conifers where branches are strong excurrent with no branch collars. *Source:* Mark S. Ashton **(b)** A photographic example of natural target pruning (right) and close pruning (left) in oak. Note the much larger wound area and potential source of infection in close pruning. This method is not recommended for trees with branch collars. *Source:* **(b)** US Forest Service.

Effects of Pruning on Tree Growth

Some pruning focuses on removal of dead branches. Because the branches being cut do not have any foliage, their removal will not reduce overall tree growth. However, pruning is often used for removing live branches (called **green pruning** or **live pruning**). This method is generally used for one of two situations: (1) where wide spacing among trees delay canopy closure, so that live branches persist and grow large in diameter; (2) where management plans call for limiting the size of the knotty core in young stands, regardless of stand density. A balance is needed between removing branches to stop knot formation in the lower stem, yet retaining enough branches to maintain foliage for rapid overall tree growth. A good biological measure for assessing this balance point would be the amount of leaf area lost by a tree from pruning, relative to the total leaf area of the tree before pruning. However, this is a complicated measurement for field operations. Instead, the change in crown length before and after pruning provides a useful substitute that can be quickly measured in the field.

Using crown-length measurements, several pine species were found to have little or no growth decline after live pruning, but only if pruning was limited to the removal of 25–35% from bottom of the crown (Pinkard and Beadle, 2000). Similarly, a number of studies of Douglas-fir, reviewed by O'Hara (1991), demonstrated that up to about 33% crown-length removal showed only small (0–10%) reductions in diameter growth, whereas crown removal of 50% or more caused from 10% to more than 40% diameter growth reduction.

The results of these studies have considerable variability, with some of it likely being linked to the relationship of crown length and canopy structure. With a young open-grown stand, there is active foliage throughout the crown, even in the lowest branches. As the canopy closes, the lower part of the crown becomes shaded and branches begin to decline in vigor. These branches produce little carbohydrate to export to the rest of the tree; they are barely able to maintain themselves. Thus, pruning the lower 33% of the crown of a tree in an open stand would reduce overall tree growth rate more than pruning the lower 33% removal of a tree crown in a closed stand, where the lower branches do not contribute much to tree growth in any case.

Pruning affects the diameter growth more than height growth, which is expected with the higher carbohydrate allocation priority for height growth. The same set of Douglas-fir studies (O'Hara, 1991) showed that removal of up to 33% of crown length did not cause a decline in height growth, but 50% removal or greater showed significant loss in height growth. This is a critical matter because reduction in the height growth of pruned crop trees means that those trees may become overtopped by unpruned trees with larger crowns. Thus, pruning of more than 50% of crown length would generally be counterproductive. There are a number of other growth responses that may occur after trees have been green-pruned.

1) When substantial foliage has been removed from a tree, it will produce additional foliage in the crown, resulting in a short-term increase in biomass growth. This complementary foliage production appears to be a response that rebalances the shoot-to-root ratio of the tree (having just become unbalanced because of the pruning of live shoots). This response partly limits the reduction of aboveground tree growth (Pinkard and Beadle, 2000).
2) Another growth response is that of **epicormic branching**, in which new shoots develop from dormant buds under the bark of the main stem, or from new buds that form in the callus tissue around the pruning wound. These sprouts will create knots if they survive and grow into large branches. However, epicormic shoots generally will not be numerous if pruning is only moderate in intensity, and if the trees do not have exposure to direct sun (Collier and Turnblom, 2001; Waring and O'Hara, 2005).
3) The removal of live branches from the lower part of the stem will reduce growth in that area, resulting in a less-tapered (more cylindrical) stem shape.
4) There has been a long-lived hypothesis that live branches control the wood-quality characteristics of the stem at the point where the branches are attached to the stem (Larson, 1963; Jozsa and Middleton, 1994). However, more recent research has shown that live branches have little or no effect on wood density or tracheid length (that is, the juvenile–mature wood transition) at the location of the branches, so pruning will not change those characteristics (Gartner *et al.*, 2002).

Pruning Equipment

To make pruning worthwhile for producing high-value timber, it generally is necessary to produce a log that is 16 ft (4.8 m) in length and has a minimum radius of 4 in (10 cm) of clear wood outside the knotty core of the stem. Thus, the total pruning height should be about 18 ft (5.4 m) to provide for the stump and trim allowance. Pruning tools must be able to reach that height, or a combination of tools might be used, some for low pruning and others for high pruning. The most common tools (Fig. 19.6) are either saws with curved blades or clippers mounted on long handles (telescopic or segmented). Sharpened blades (without teeth) on long handles are used to plane off branches with a downward stroke. It is also possible to use hand saws from ladders, but moving ladders around in forest stands is cumbersome. Arborists with tree-climbing skills can prune branches at any height, but the cost would be prohibitive for timber-management purposes.

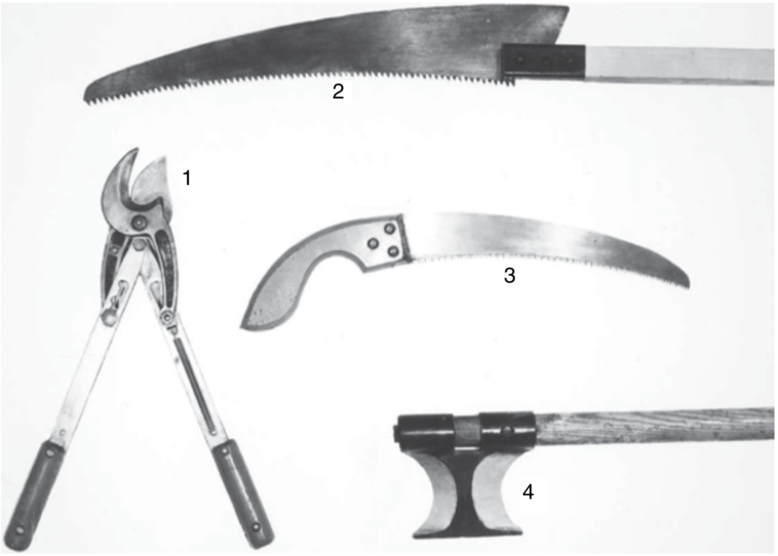


Figure 19.6 Typical tools for pruning forest trees: (1) shears designed for close pruning, (2) the blade of a pole saw, (3) a hand pruning saw, (4) a pruning tool that cuts on the downward stroke. *Source:* US Forest Service.

The most substantial innovation for pruning has been the development of small power saws. These have a small chainsaw bar mounted on a telescoping pole, with a small gasoline engine at the base of the pole, held by the operator. However, safety concerns have precluded the use of these saws in many companies. Pruning machines have also been developed that power themselves up the tree, cutting branches as they go. The operator stays on the ground, directing the machine with remote controls. These work best on cylindrical trees with only minor bumps or other irregularities. When they work well, trees can be pruned very high up the stem. So far, most North American tree species have been found to have enough stem irregularities that these machines are of little use.

Pruning the lower half of the 18-ft (5.4-m) log is easy enough, but the time and cost of pruning the upper half are two to four times greater, using any of the available tools. It would be more economical to prune branches on the first half-log on more trees, rather than to prune fewer trees to the full-log height, but 9-ft (2.7-m) logs would generally not be acceptable for standard conifer log sizes (O'Hara, Larvik, and Valappil, 1995). This is not a problem with high-quality hardwood logs, which are accepted in shorter lengths, but there generally is less need for pruning.

Effects of Knots on Wood Products

Knots produced while branches are still alive are known as **live knots**, **inter-grown knots**, or **red knots** (they are usually reddish in color). The term "inter-grown" refers to the intermingling of the stem wood and branch wood growth in the lower half of the living branch. Live knots are also called tight knots because the attachment in the lower half of the branch is sufficient to keep them in place when they are in a piece of dried lumber. The knots that are formed after branches have died are called **dead knots**, **encased knots**, or **black knots**. The term "encased" means that the knots are trapped inside the living stem, without any structural connection to the stem. They often have resin deposits and are partially decayed, so they generally are black in color. Thus, dead knots are often loose knots, because they are likely to fall out of a piece of dried lumber (Figs. 19.7, 19.8).

Artificial pruning is expensive, so there must be a substantial price premium for knot-free boards or veneer in order to make the practice worthwhile. The defects caused by knots have different impacts depending on whether the wood is for construction lumber or finished products. Construction lumber is almost always from softwood species. Even though knots substantially reduce the load-bearing strength of a board, the construction industry solves this problem by requiring the use of thicker lumber to compensate for the presence of knots. However, there are limits to the type (tight or loose), number, and size of knots for load-bearing construction lumber.

Certain conifer species are much more highly valued if they are knot-free. Hard pines and Douglas-fir have strong wood, but it is too coarse for most finishing purposes. Knot-free (or nearly knot-free) logs of these species are used for the exterior surface veneer of construction plywood (interior layers can have knots). The surface veneer ideally should be completely clear, but a semi-automated method has been developed in plywood mills to cut out knots in the veneer, and replace them with pieces of sound wood. Clear wood of these dense conifer species is also used for large long beams that meet stress-grading specifications for spanning large distances in building construction.

Other conifer species that are valuable as clear wood are those in the medium- to low-density range, and where

there is only a moderate difference in color between early and late wood. These species include white pine, spruce, larch, hemlock, cedar, and true firs. Some of these are used for furniture, paneling, and shelving, and some are used for milled products that are shaped for trim work.

Most hardwood lumber is used in short lengths, for furniture, flooring, and finish wood. Much of its value is in the visual quality of the wood. A small tight knot is considered as serious a defect for hardwood finish grading as a large rotten hole from a black knot. To a certain extent, the furniture or flooring boards can be cut into short lengths to eliminate the knots. However, the thin sheets of peeled or sliced veneer for interior paneling must have large areas of clear wood, and in this case the knots cannot be cut out and replaced, as is done with construction plywood.

The problem with knots is really more important in hardwoods than softwoods because so many hardwood products depend on appearance. It is just good fortune that knots are less numerous in hardwoods. The only reason that there is more concern about pruning with softwoods is that their branches persist longer on the stem and create many more knots.

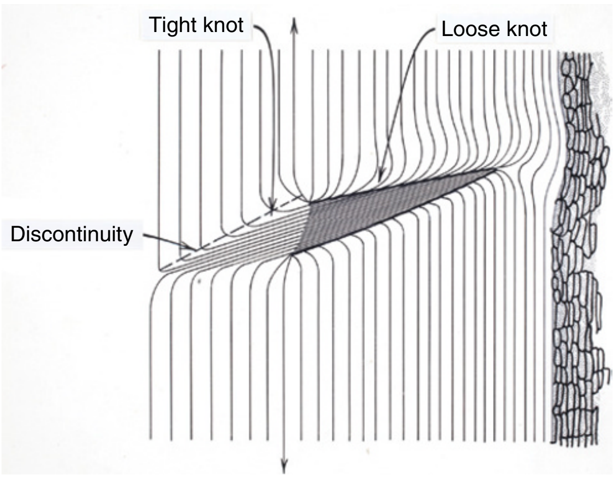
Pruning Methods for Timber Management

Conifers

Pruning is rather expensive because there is a great deal of manual labor involved. The kinds of innovations that have occurred with tree-harvesting equipment have not been duplicated with pruning equipment. In addition, the costs of pruning come relatively early in the rotation, with the return on that investment delayed to the end of the rotation. It is important to recognize this situation because it should focus serious consideration on the number of trees to be pruned, the timing of the pruning operation, and the thinning needed to keep the pruned trees growing rapidly.

Regarding the number of trees to be pruned, one standard approach is to prune only the trees that will be carried to the end of the rotation, plus an additional 10–20% to account for damage or loss of crop trees. This would generally amount to 40–100 trees/acre (100–250 trees/ha) to be pruned. The decision about the specific number within this range depends on the target diameter selected for the trees at the end of the rotation, and the crown area of those trees. It is not necessary to have a stand that could produce a fully closed canopy of pruned crop trees

(a)



(b)

Figure 19.7 **(a)** An illustration of a radial section through a pine branch that persisted for many years after its death. The branch is thickest where it joined the stem at time of death. Note that the annual rings of the branch after death turn inward without joining the wood of the branch. Even when the branch was living, the fibers of the upper part of the branch did not actually link with those of the main stem, though they appear to do so, if one examines a section of this kind. The arrows at the top and bottom mark the last annual ring formed before the branch died. *Source:* Yale School of Forestry and Environmental Studies. **(b)** A photograph of a red knot in pine. The drying process has caused the red knot wood to rupture, given its different wood density and structure and therefore inherent tension in drying, as compared to the normal stem wood. *Source:* US Forest Service.

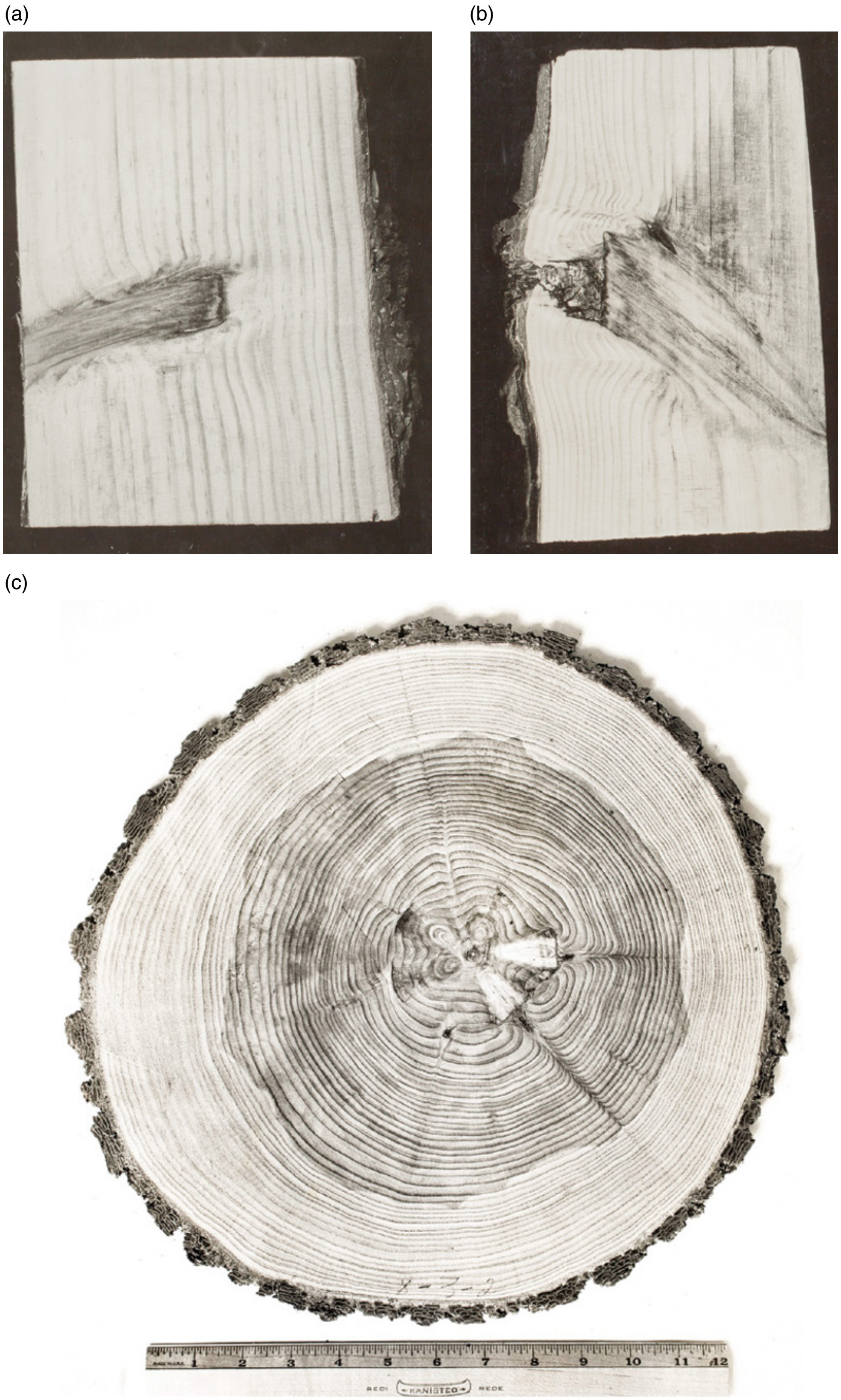


Figure 19.8 Photographs of **(a)** red knot in spruce lumber, **(b)** black knot in oak lumber, and **(c)** a cross-section of red knot of pruned spruce. *Source:* **(a–c)** US Forest Service.

at the end of the rotation. If there are only scattered trees of high quality, then just those few trees can be pruned.

It is important that pruning be coupled with a thinning program that is aimed at maintaining rapid diameter growth of the crop trees. This is necessary in order to heal the pruning wound quickly and to produce substantial amounts of clear wood to repay the high compounded cost of an operation that takes 10–15 minutes per tree with a wait of 15–50 years for the financial returns. The most logical thinning method would be crown thinning, to focus on the release of growing space for each of the pruned crop trees. This could also include thinning to release the acceptable (but unpruned) sawtimber trees that will be cut before the end of the rotation. Thinning could be more intense, including cutting all trees except those that are pruned. In some cases, dominant thinning may be needed to remove tall trees with large branches and poor stem form; then the choice of crop trees for pruning is from among the codominants and intermediates of the stand.

With the question of when pruning should be done, an aggressive approach would be to live-prune a young stand before canopy closure, keeping to the guidelines of 33% as a maximum for removal of crown length. This guideline may limit pruning to less than the full 18-ft (5.4-m) log height because the trees would have to be at least 54 ft (16.3 m) tall. However, waiting until the trees reach that height would allow the branches on the lower stem to grow larger and increase the area of the knotty core. The solution to this problem is to use two or more pruning operations, or **lifts** (this term comes from the idea of lifting up the bottom of the canopy by pruning). In order to keep the knotty core small throughout the length of the stem, the first lift could remove the branches up to 9 ft (2.7 m), and several years later (after additional height growth and crown development) the second lift would remove the branches up to a height of 18 ft (5.4 m).

A more moderate approach would be to allow the stand to develop to the point where branches have died up to the height of one 18-ft (5.4-m) log. This regime would include pruning only dead branches, thus avoiding any problems of growth reduction or epicormic sprouting. Two or more lifts could be used; pruning could follow the progress of natural mortality of branches as it proceeds up the height of the tree.

A key aspect in planning a pruning program is an economic analysis relating to the time between the pruning operation and the harvest of pruned trees at the end of the rotation. Trees are often pruned when they are about 5–10 in (12-25 cm) diameter at breast height (DBH), and are grown to 16–22 in (40–55 cm) or more for final harvest, but the times to reach those sizes differ drastically among species and climatic regions. With eucalyptus plantations in tropical regions, pruning usually occurs before age 5 years, with a rotation length of 20 years, so there is only about a 17-year time span for the pruning investment (Montagu, Kearney, and Smith, 2003). With coastal Douglas-fir, pruning may occur at about age 20, with a rotation age of 60 years, extending the investment period to 40 years (Fight, Bolon, and Cahill, 1993). Growth rates are slower on dry sites, such as with ponderosa pine in the Black Hills. With a rotation of about 100 years, pruning operations might be delayed to about age 50 or 60 years into the rotation. This late timing of pruning is based entirely on the length of the investment period. If a ponderosa pine stand is held for more than 40 years after a pruning operation, then the effect of compound interest will cause the return on the pruning investment to decline (Smith, Kurtz, and Johnson, 1988). Very little pruning is done in the southeast in general, but when loblolly pine is pruned, it is done immediately after the first thinning, only on the crop trees. Note that the details of these economic analyses vary with the fluctuation in overall economic conditions. They are given as examples here to present the basic principles of the economics of pruning. Although it is possible to waste money on pruning, under some circumstances the combination of investments in pruning with thinning and good diameter growth can provide some of the highest long-term returns available in timber-production silviculture.

Hardwoods

Most of this chapter about pruning has dealt with conifers. Many hardwood forest types regenerate in very dense natural stands, causing rapid canopy closure and branch death. These dead branches tend to decompose quickly, so there is usually little need for pruning. However, when plantations of hardwood species are established, large persistent live branches occur because of slow canopy closure, just as with many conifer stands. Black walnut plantations are a good example. They have been established by private landowners in the central US to produce highly valuable furniture wood. Stands are planted at low densities of 40–100 trees/acre (100–250 trees/ha), so pruning is required to produce knot-free wood. Similarly, some eucalyptus species in tropical plantations are pruned because of the slow shedding of branches. These are planted at a total density of 440 trees/acre (1100 trees/ha) with the pruned trees in the stand having a density of 40–120 trees/acre (100–300 trees/ha).

While hardwood stands are not the focus of most pruning, it is good practice to prune any stray branch or epicormic sprout, but only on high-value hardwood stems. This would generally be a strategic cleanup of a small number of branches, rather than a major pruning operation. However, broken or pruned branches on maple species create a special problem. Maple species, especially sugar maple, are quite valuable if the wood is white, rather than brown. Whenever any branch larger in diameter than about 1 in (2.5 cm) in diameter dies or is cut, it becomes an entry point for bacteria that turn all of the

existing stem wood below the height of that injury into undesirable brown heartwood (Shigo, 1984b). Thus, all pruning of maples should be done when the trees are small, and then they should be released from competition by thinning to prevent branches in the crown from dying.

Pruning for Non-Timber Objectives in Forests

Pruning can be used for objectives other than reducing knot formation in sawlogs. One of the most important uses is to control white pine blister rust, an introduced fungus that infects all of the white pine species. The fungus has two hosts: *Ribes* species (understory woody plants), and white pines. If the spores from the fungus on the *Ribes* plant are blown onto the lower branches of pine saplings, they infect the branches and in some cases will grow along the branch into the main stem, eventually girdling it. It has had a much greater impact on western white pine than eastern white pine, essentially eliminating it as a large tree in the northern Rocky Mountains. If the bottom branches of western white pine are pruned up to 10 ft (3 m), this reduces the opportunity for the fungus to colonize the tree branches, and thus reduces the probability of blister rust infection on the stem (Hunt, 1998). It is important to remove the branches early, so a smaller version of a two-lift pruning operation is the best method, with removal of the bottom branches to 4 ft (1.5 m) in height as soon as it is possible, while retaining two or three whorls on the tree. Then, after additional growth, pruning can continue up to a 10 ft (3 m) pruning height. Across the west at high elevation, white pines are being impacted by the rust or it is just starting to take hold. These species include whitebark, limber, southwestern white, Rocky Mountain bristlecone, foxtail, and sugar pines (O'Hara, Grand, and Whitcomb, 2010; Crump *et al*., 2011).

Pruning can also be used to produce a more open stand that creates a greater vista beneath the forest canopy. For recreation areas, low pruning allows people to walk more easily through a stand, especially in dense stands of species such as spruce, with many stiff branches. In these kinds of young dense stands, pruning to about 6 ft (1.8 m) in height is sometimes done just to make it possible to move around in the stand for silvicultural work; this use of pruning is called **brashing**. The risk of wildfires can also be reduced by pruning branches in some cases; this is discussed in more detail in Chapter 18.

Techniques of Pruning Open Grown Trees Within Urban Environments

Street Trees and Park Trees

All planted trees in urban environments need a pruning program, though rarely is this done in the right way or at the right time. Pruning considerations include: (1) reducing the risks of limb failure that can be caused by included bark or some other defect in a large tree; (2) increasing the clearance from low overhanging limbs and branches that can be obstructions for vehicles and people; (3) removing dead, dying, and diseased tree limbs before they become a falling hazard; and (4) ensuring tree form and growth will conform to the desired space and away from power lines and buildings. Taken together, all these risks can be reduced by having a strong pruning program that starts immediately after planting the tree.

Understanding Growth Form

Trees of all kinds have very different growth forms when grown in the open (Fig. 19.9). Understanding the form of a tree and developing a pruning program that is sympathetic with the tree's natural tendencies for growth, is both a very important factor to recognize and a difficult one to practice without knowledge and experience. Yet it is probably the single most important attribute of maintaining the aesthetics of the tree in the long term.

Given overall considerations to tree form, there are several other important factors for pruning that must be included. Pruning programs need to aggressively plan, early in the program of a planted tree, to remove future low limbs, limbs with the potential for bark inclusion, and codominant stems. The first two factors, low limbs and bark inclusion, are obvious, but removal of codominant stems is less so. Codominant stems often grow at angles that make them extremely susceptible to bark inclusion and breakage later, when the tree is mature, by wind and loading stresses from snow and ice.

The Mechanics of Pruning

The secret to pruning is to start the program early after the newly planted trees have been established. Setting the branches and form at that time will save years of maintenance and care when the tree is large and mature. Most pruning should be centered on either doing a reduction cut or a heading cut. A **reduction cut** is the removal of a stem that is becoming codominant by shortening one of its lateral branches. This requires cutting back to a lateral branch that is at least one-third the diameter of the stem cut. Thus, the term "reduction" (Fig. 19.10), where you reduce the dominance of the branch to grow in relation to the competing codominant stem, but allow its continued growth through the lateral branch that has been left. A **removal cut** is exactly the opposite, where the branch that remains is the dominant and the smaller is removed. This pruning technique is practiced to accentuate or prefer a dominant stem. A **heading cut** (**topping**) is usually inappropriate because it ignores the form of the tree and promotes multiple sprouting. However, if the tree has been damaged by wind and ice, this kind of pruning may be appropriate to increase foliage.

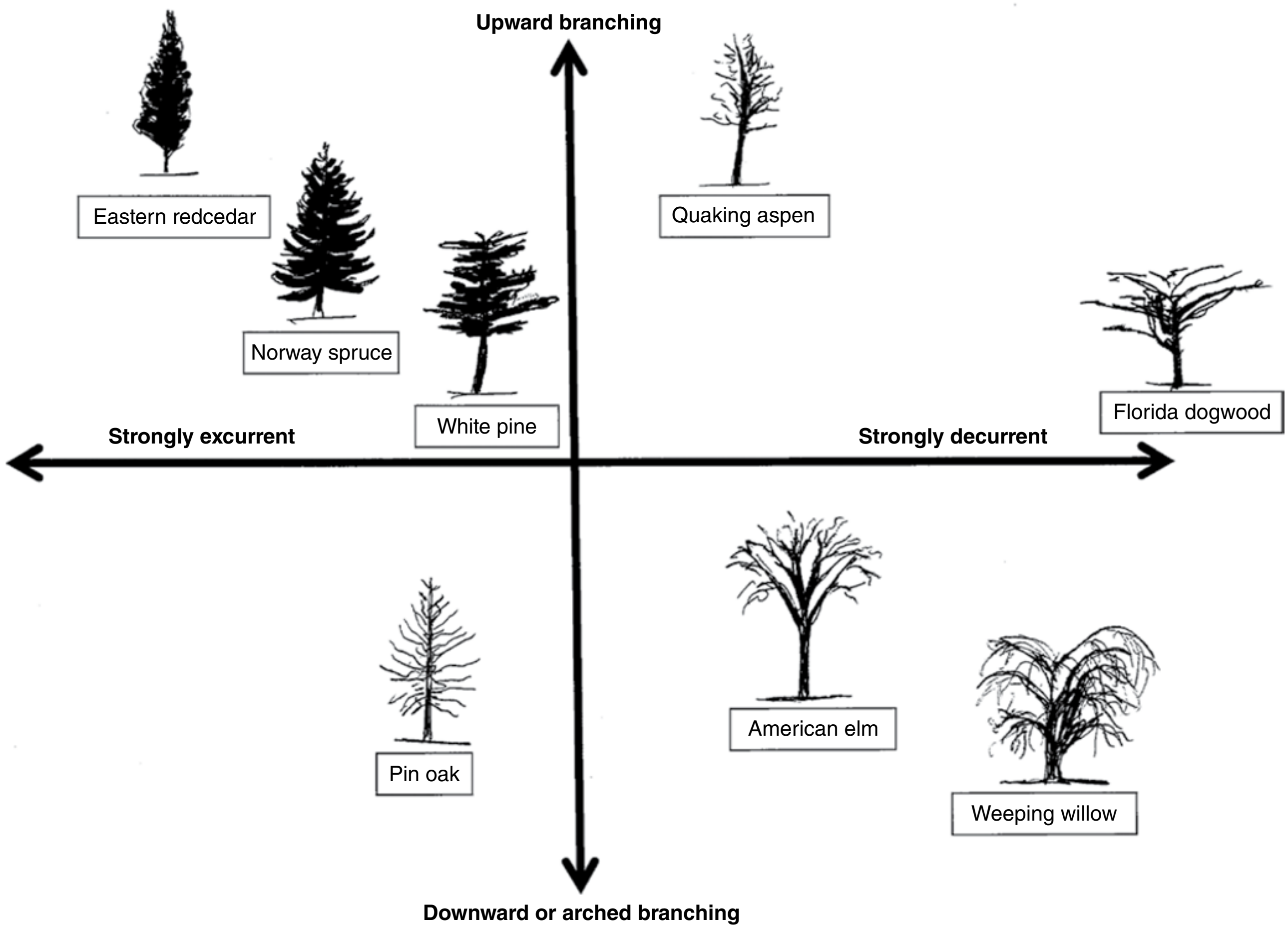


Figure 19.9 Tree species' growth forms change in relation to upward and downward hanging branch forms and in relation to the strength of stem dominance between strong excurrent growth versus decurrent and branched growth. *Source:* Mark S. Ashton.

Applying a small reduction or removal pruning to a tree is straightforward. More careful attention needs to be applied for large limbs of trees. In urban circumstances, with the dominance of hardwoods, the pruning approach mostly uses the natural target method, as explained in prior sections. It is important to prune outside of the branch collar when it is visible, and if it is not visible, to cut at an angle equal and opposite to the branch bark ridge outside of where the angle of the branch makes an abrupt turn. When large limbs are to be cut, it is also necessary to make a notch above where the final pruning cut will be made, and then to cut the stem above, such that when the stem falls, any holding wood that is ripped off is stopped at the notch (Fig. 19.11). After this, the normal approach to making the pruning cut can be made without concern that the limb will rip off, creating a larger and uneven surface area for occlusion and healing.

There is no need to apply paints, tars, or oils to the cut surface. This usually speeds up decay from water and moisture accumulating underneath. It is best to leave the surface to dry, and to have a surface where water can run off easily. In cases where rot has already set in, the best that can be done is to expose as much of the wood surface to the air and ventilation. The more humidity and moisture that accumulates in a cavity, the greater the proportion of rot.

A Pruning Program

To implement an urban tree pruning program there needs to be a clear set of objectives for two broad categories of trees. First, newly planted trees and young trees from which you can ensure a proper program that greatly reduces maintenance and risk at maturity. Second, a program to reduce risk and improve the health of existing mature trees that have not had a pruning program and so need greater care. Objectives when pruning young trees usually can be characterized as: (1) reducing future risk; (2) reducing the potential for future understory and overstory space conflicts; and (3) improving the future aesthetic. Objectives when pruning mature trees can be characterized as: (1) reducing the existing risk of hazard

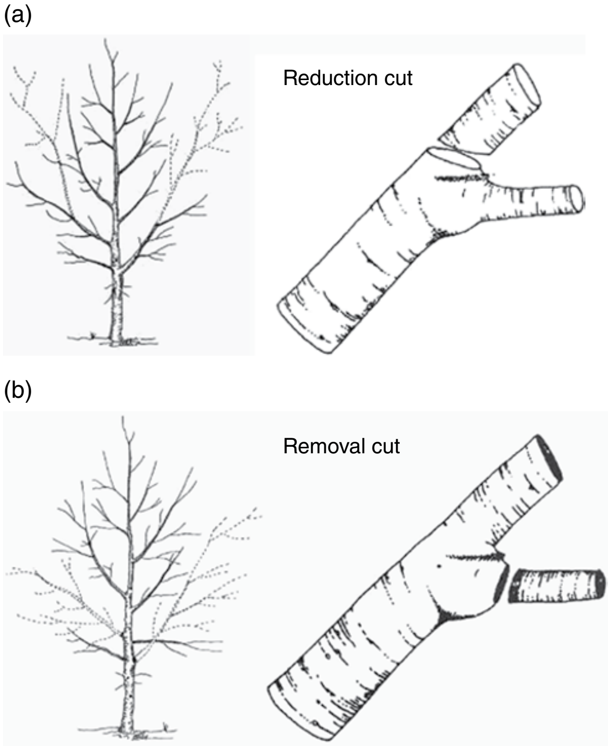


Figure 19.10 (a) A reduction cut that shortens the length of the stem by pruning back to a smaller limb. (b) A removal cut prunes a branch back to the trunk or parent branch. *Source:* (a, b) Adapted from The Urban Forest Hurricane Recovery Program, University of Florida..

branches; (2) reducing the existing space conflicts with vehicles, buildings, and power lines; (3) reducing shade; and (4) maintaining or increasing the tree health.

A pruning strategy for young or newly planted trees is to first develop a **string tree structure**. This means selecting for dominant leaders and well-spaced smaller branches to reduce future branch breakage when mature. This entails a program that includes mostly reduction cuts that promote more growth into the unpruned leaders. Structural pruning should occur regularly and iteratively to reduce stem codominance (every few years) before the tree reaches its mature tree height. Using Gilman's (2012) guide, there are five strategies for structural pruning:

1) develop a dominant leader;
2) identify the lowest branch that will be permanent in the tree at maturity;
3) prevent branches from becoming too large or developing upright growth below the lowest branch that is identified to be part of the permanent canopy at maturity;
4) space the main lateral branches along the dominant stem leader and ensure they are less than one-third in size as compared to the main stem;
5) reduce growth on branches with bark inclusion, and eventually remove.

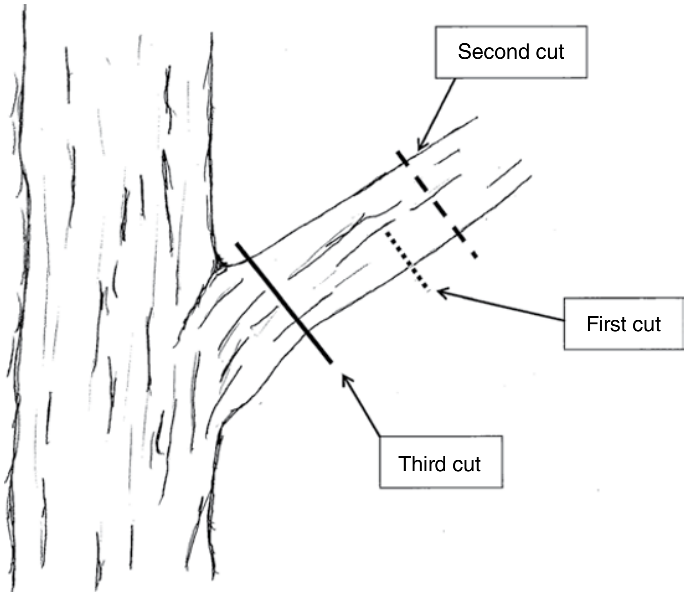
Structural pruning should be thought of as a training program so that young trees will clear power lines, buildings, and transit space beneath, with elegance at maturity. Parts of the tree that potentially could weaken the branch structure are removed, and a branch spacing is promoted that will yield an even distribution of foliage when the tree is fully grown. If left untreated, defects and a poor crown structure will only create a much more expensive maintenance problem later on. One point to consider is the idea of top-pruning street trees at the time of planting, to reduce leaf area and reduce transpiration stress on the roots. This is ill-advised. If this must be done then it is better to prune the codominant stems by reduction cuts.

For mature trees that have fixed structure from their past growth history, the forester should take a different approach to pruning. In fact, at maturity, a pruning strategy needs to be more specific as to species, site, and form. Pruning needs to switch from a focus on structure to one that removes dead and dying limbs (termed **crown cleaning**), and raising, thinning, and reducing the canopy when appropriate, to ensure the tree matches the growing space. A tree does not need a uniform pruning treatment. A single tree can have several pruning treatments (i.e., thinning versus reducing) to accommodate a shading effect and a structural weaknesses that are apparent in different parts of the crown. The amount of pruning done on a tree (the pruning dose) is generally never more than one third of the leaf area, and the heavier the dose, the greater the interval of time between pruning treatments.

Pollarding

Interestingly, the use of pollarding is a common tradition, particularly in the street trees and courtyards of the old cities and villages of Europe. It can only be suspected that it is a tradition which has been maintained from the agricultural coppice systems of medieval times and has become part of the aesthetic psyche of the region. However, pollarding is a useful way of confining a large tree to a smaller space. Planted trees that are intended to be pollarded also need to have a pruning regime that creates the eventual structure of the mature tree which is then pollarded at repeated intervals of time. To prune a tree that will become pollarded, one again has to focus the early pruning on developing the symmetrical structure of the tree (Fig. 19.12). This entails almost the opposite strategy as compared to pruning to the form of the tree. The leader is top-pruned at the preferred height for the lateral buds to branch out. After developing a symmetrical and almost radial branching pattern, the lateral branches are topped to initiate a second set of lateral branches from the nodes of each topped branch. This may be the crown size that is ultimately desired for the pollard. If not, a third iteration of branches can be topped.

(a)



(b)

(c)

Figure 19.11 **(a)** The three stage process of pruning a large limb. The first cut is made up from the final intended pruning cut. It is made under the branch so that the second cut severs the branch initially, to remove the weight and ripping effect as the limb is pulled down. If the branch does rip downward, it is stopped by the first cut. The third and final cut can then be done with precision without fear of tearing. *Source:* Mark S. Ashton. **(b)** A photograph of a large limb properly pruned and with a well-formed callus developing over the wound. **(c)** An example of a very poor pruning of a large limb that cut into the branch collar. The callus has failed to heal over the wound and decay has spread outward. *Source:* **(b, c)** US Forest Service.

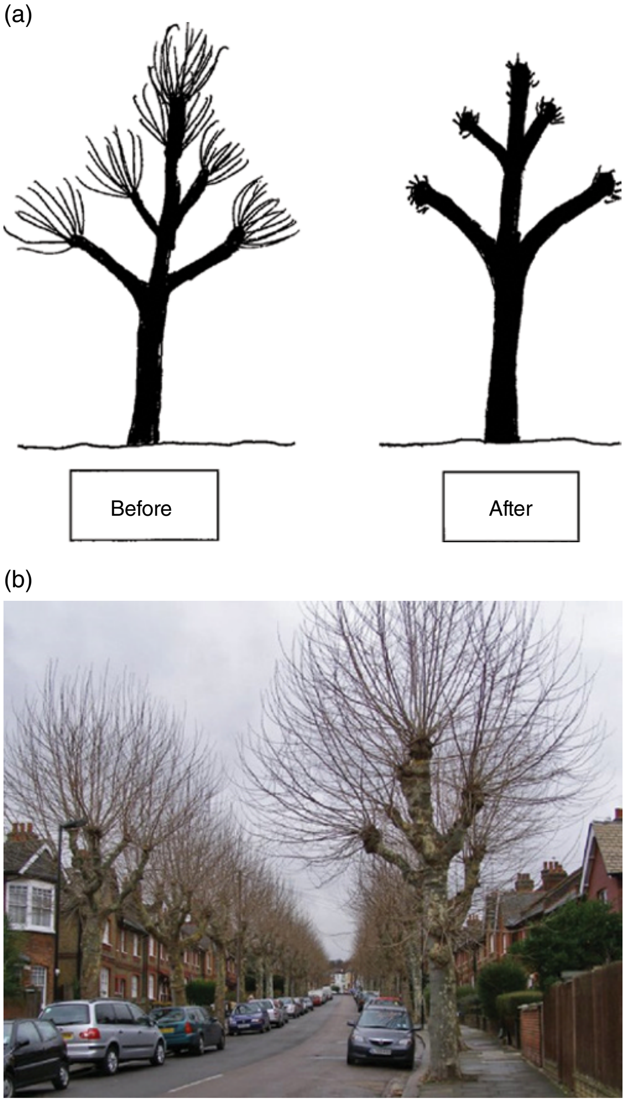


Figure 19.12 **(a)** A graphic depicting the before and after effects of pollarding. *Source:* Mark S. Ashton. **(b)** An example of pollarded London plane trees on a suburban London street. *Source:* I. M. Chengappa. Reproduced with permission from I. M. Chengappa.

Training and Pruning Fruit and Shade Trees in Orchards and Agroforestry Systems

When describing pruning regimes for fruit and nut trees, the species must be suited to pruning that maximizes flowering. Many fruit and nut trees are conducive to pruning because their branching architecture can be promoted to spread and their flowering is behind the vegetative shoots (e.g., apples, pears, peaches, cherries, coffee). In these circumstances, trees are conducive to both training and pruning. However there is a group of fruit trees that have flowers and fruits at the terminal ends of their shoots where pruning is not encouraged (durian, breadfruit, jak, mango, avocado). These species do best when grown freely in open or closed canopied conditions and where pruning is minimized for ensuring a strong structural architecture with no rot or disease.

Like street trees and open-grown park trees, there are two phases for fruit trees that should be pruned. When young trees are planted either in orchards or in agroforestry systems, there is first a program of training the trees' growth to conform to a branching structure that will maximize fruit or nut production. The second phase is the repeated pruning regime itself that maintains the structure and maximizes the ratio of reproductive to vegetative shoots.

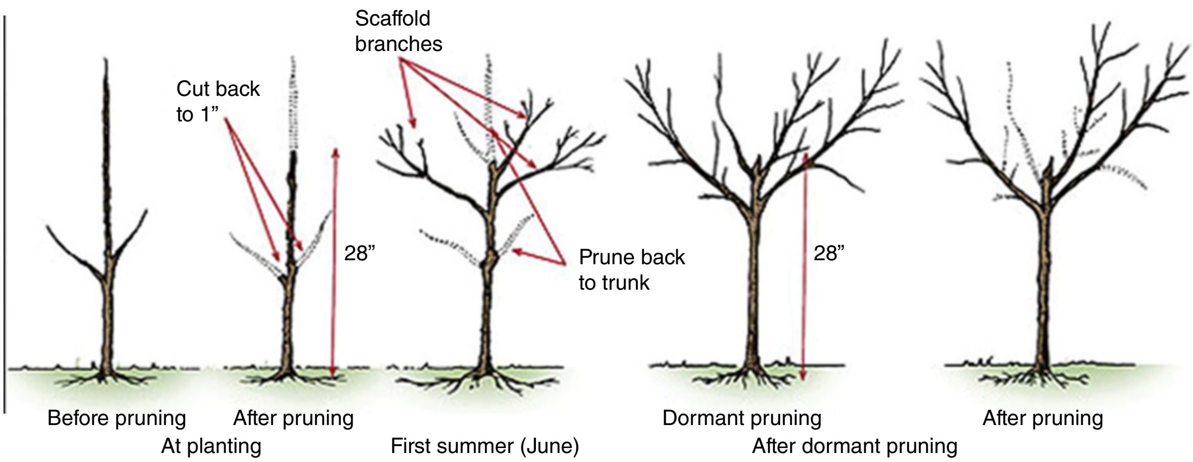
Training Fruit and Nut Trees

The main objective of training a young stem by pruning is to create a branching framework that will significantly increase the fruit productivity of the tree and allow the tree to live considerably longer without serious infections or limb breakage. For this, the tree framework needs to be created in such a way as to maximize light penetration deep into the crown, and therefore to maximize leaf and flower bud production per unit area of ground, that the tree crown occupies. This means that first, a single dominant leader needs to grow to a determined height that both logistically allows access to the canopy of the plant and allows for some mobility underneath. At that height, the leader is headed (topped) at a position such that the buds immediately beneath will be released laterally rather than upright. Too many upright branches can result in branch breakage in the same manners as street trees. This is the start of the tree structure that will develop into the **scaffold branches** that will set the framework of the tree (Fig. 19.13).

Developing a Pruning Program

Pruning the shoots that develop off of the scaffold branching framework of the tree strongly influences the number and size of flower buds produced each growing season. There are three kinds of pruning treatments to maintain the structure of the tree and to ensure enough allocation of shoots to reproduction. **Thinning cuts** remove the entire shoot back to its base. This technique re-directs growth to other branches and other parts of the tree, much like a reduction cut will do for a street tree. The **heading cut** made in young shoots (first year) removes the top of a new shoot, promoting the vigorous release of the buds immediately toward the top end that result in lateral branching. Heading cuts made in older wood is chiefly done to move the crown back into its

(a)



(b)

Figure 19.13 **(a)** A schematic illustrating the development of a structural framework for a fruit tree with its growth. **(b)** An old apple orchard still very productive using the original scaffold branches that created the structural framework for the tree. *Source:* **(a, b)** Mark S. Ashton.

allotted space. **Bench cuts** remove all the vegetative vigorous upright shoots back to the scaffold branches of the original framework. They are chiefly done to open up the center of the tree to allow more light in and to open up the branches.

For most deciduous fruit and nut trees, flower buds develop on the lower parts of young vegetative shoots the previous year. Heading these shoots annually, and benching periodically, maximizes light penetration for best flower and fruit development and promotes air circulation and lowers humidity, making fruits less prone to disease and rot. The best time of the year to prune is during the dormant period when all the carbohydrates are stored in the roots and main stems. Heavy dormant pruning can lead to excessive vegetative upright sprouting that creates excessive shading of the interior canopy and poor fruit set. There are some general rules of thumb for dormant season pruning: (1) prune as late into the dormant season as possible; (2) prune the late-blooming species first and the early-blooming last; and (3) prune the older trees first and the young trees second. All these rules are to ensure a methodical and strategic way of developing a pruning regime that will maximize particular yields that vary by species, size, and age of tree within an agricultural or orchard system. Summer or growing-season pruning tends to be less invigorating and can reduce tree growth and should be limited to removing the current season sprout growth with thinning cuts. Finally, all pruning cuts need to be as flush to the remaining branch as possible to ensure rapid healing.

Pruning for Leaf Production

To maximize leaf production in plants that are conducive to sprouting such as hedgerows and Christmas trees (Fig. 19.14), the pruning regime is the reverse of trying to maximize flowering buds. Instead of heading cuts that remove a significant length of shoot to release flower buds behind, pruning should be focused on heading cuts that just take off the ends, releasing mostly vegetative buds. To do this across all the outer shoots of the crown efficiently, the pruning technique used is called **shearing**. Shrubs and trees that create hedgerows are sheared in this manner after their main branching structures have been set by training. Tea shrubs are manually sheared every week to continuously produce and release vegetative shoots that are plucked (Fig. 19.15). The only way to maintain and reinvigorate the shearing process in shrubs and trees is to thin back individual stems to the base, to allow more light into the center of the crown for new stem development, or to brash all the branches back completely to the base of the root collar of the stem to promote new sprout growth. This is often done at periodic intervals for sheared shrubs that get worn out and lose their capacity to produce new leaves and stems.

Figure 19.14 Pruning Christmas trees requires the development of a conical form done by shearing the sides of the tree with a very sharp knife that clips the lateral branches. This releases more buds making the form of the tree "bushy." The stem growth of the leader is regulated by pruning to a length that will reduce the legginess, forcing the tree to release lateral branches at shorter intervals. *Source:* D. Cassens. Reproduced with permission from D. Cassens.

(a)

(b)

Figure 19.15 Tea bushes being plucked for tea. **(a)** Tea plant shoots require a very refined shearing in which, every week, two leaves and a bud are pruned evenly across the whole shrub and across all shrubs together. **(b)** Pruning in action – harvesting the tea leaves. *Source:* **(a, b)** Mark S. Ashton.

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20

Release Operations in Seedling and Sapling Stands

Introduction

Release operations are designed to provide growing space for desirable tree seedlings, saplings, or poles, by removing competing vegetation (trees, shrubs, vines, herbaceous plants, or other seedlings and saplings). There are two distinctly different situations that call for release operations. In the first situation, **cleaning** and **weeding** are carried out as a standard part of tending newly established stands. A variety of herbaceous and woody plants may germinate along with the desired regeneration or they may already be present on the site. These plants can reduce regeneration growth rates by competing for light, water, and nutrients. **Cleaning operations** focus on **removing only the overtopping vegetation** around the selected crop trees. **Weeding operations remove all plant competition** that may be growing above, beside, or below the crowns of all the young desirable trees.

The newer more general terms **forest vegetation management (FVM)** and **vegetation control** are also commonly used to refer collectively to both cleaning and weeding. These treatments can be used to release seedlings of any desirable species, for timber production, forest restoration, or other purposes. Their principal mode of control is with herbicides for timber plantations, in order to free valuable conifer species such as pines, spruces, and Douglas-fir from competition (Lautenschlager *et al*., 1998; Thompson and Pitt, 2003; Talbert and Marshall, 2005; Fortier and Messier, 2006; Wagner *et al*., 2006).

In the second situation, **liberation** treatments are also used to release young stands that are below the seedling, sapling, or pole stage. In this case, the competing plants are distinctly older, overtopping the trees and vines. These stand conditions arise when seedlings become established beneath a partial overstory canopy. These conditions can exist after a selection regeneration method, a high-grade cutting, or other harvest operations (usually poorly planned). Liberation treatments are commonly used in selection regeneration methods to free seedlings that were established from the creation of canopy openings made by prior entries around which the overtopping canopy has grown in. In addition, liberation treatments can often be done with enrichment planting of seedlings that have been planted beneath a forest canopy. Liberation treatments can be used to remove most or all of the overstory trees, releasing the established regeneration. These operations are used to remedy problem situations, and are usually not part of standard silvicultural planning. Liberation treatments will be described at the end of the chapter.

Competing Vegetation

It is useful to classify the variety of plant species that can make up the competing vegetation in a stand of valuable regeneration (Balandier *et al.*, 2006). Plants are grouped by size and growth habit, because these factors control the type of competition that will be present:

- **grasses:** grass, sedge, and rush species, all with dense, fine roots and narrow-bladed leaves;
- **forbs:** herbaceous (non-woody) dicotyledonous plants such as fireweed, composites (solidago, aster), and ferns;
- **short woody plants:** small shrubs (greenbrier, barberry) and semi-woody brambles (raspberries, blackberries);
- **tall woody plants:** seedlings from competing trees, sprouts from canopy trees, woody vines (kudzu, wild grape), and tall shrubs (autumn olive);
- **canopy and subcanopy trees:** mature trees in the main canopy and subcanopy, and high-canopy lianas and vines.

These plant groups (or **vegetation components**) present considerably different kinds of competition for crop-tree seedlings (Balandier *et al.*, 2006). Grasses have a shallow but very dense system of fine roots and can compete intensely with crop-tree seedlings for water and nutrients. However, their thin, erect leaves generally do not cast much shade on tree seedlings. If tree seedlings can establish roots through the dense root systems of the grasses, trees can often survive. They will just grow more slowly because of grass competition for nutrients and water.

This can be a problem with planted seedlings in old-field pastures, or with plantation establishment of spruce in competition with *Calamagrostis canadensis* grass in the boreal forests of Canada (Hangs, Knight, and van Rees, 2002; Matsushima and Chang, 2007). The next three groups (forbs, short woody plants, and tall woody plants) have roots that are more similar to those of crop-tree seedlings, so belowground competition is on a more equal basis than when tree seedlings compete with grasses. These three groups mainly limit the growth of crop trees through shading. Competing plants that are only moderately taller than the crop-tree seedlings that create dense **low shade** on the foliage of the crop seedlings. Examples of this process are hayscented fern (*Dennstaedtia punctilobula*) in the northeastern hardwood forests (Fei *et al.*, 2010), competition between *Rubus* spp. and spruce and fir in the maritime regions of Maine and Canada (Jobidon, 2000), and salal (*Gaultheria shallon*) competition with Douglas-fir in the Pacific Northwest (Rose, Ketchum, and Hansen, 1999; Rose and Ketchum, 2003). With mature trees, shading is also the main competitive factor. However, the tall canopy creates **high shade**, which produces diffuse light that allows seedlings to survive for long periods, but with much reduced height growth (Pariona, Fredericksen, and Licona, 2003).

This classification of competition types makes it possible to better define release methods. The control of grasses that compete belowground is commonly referred to as **herbaceous plant control**, and is roughly equivalent to the traditional term of "weeding". The control of woody plants such as shrubs, sprouts, vines, and trees, which all compete by overtopping and shading other plants, is called **woody plant control**, roughly equivalent to the traditional term of "cleaning" when used selectively. Only forbs and ferns are out of place in this classification. They are treated by herbaceous control methods, but they compete through shading, which fits with the woody plants.

Concept of Free-To-Grow

The term **free-to-grow** (or **free-growing**) denotes a potential crop tree or target tree of seedling, sapling, or pole size, that is not overtopped by competing vegetation. When considering release operations, it is useful to think in terms of removing vegetation that has grown upward into an inverted cone above the top of a crop tree (Fig. 20.1). The approximate size of the cone's angle will vary with the relative height growth rates of the released tree and of the competing plants. If the crop tree is slow growing, the cone will need to be broader so that the adjacent vegetation will not close in before the crop tree expands into open growing space. The extent of release would depend on the relative growth rates of the different species present and the amount of time that would be allowed to elapse before another cleaning.

The free-to-grow concept is used as a regulatory method in some states and provinces that require stands to be regenerated within a specified time period after a final harvest cut. Generally, it is not enough to meet the standard of establishing the minimum number of seedlings per acre. The requirement is usually that the seedlings must be free to grow. Although the idea of defining the required growing space as an inverted cone is a useful silvicultural concept, other specific definitions are used as legal requirements in various locales. In general, the conceptual approach of free-to-grow would be categorized as a cleaning.

Early Use of Release Treatments

An early use of vegetation control treatments was to remove the competition of hardwood saplings and shrubs that overtop valuable conifer seedlings or saplings. When conifer seedlings were established by planting or natural regeneration, two groups of hardwoods would compete: fast-growing pioneer species that had become established at the same time as the conifers, and shade-tolerant species that were already established in the understory before the harvest. Ideally, a cleaning operation would judiciously kill those hardwoods competing directly with the crop trees, but when these species were cut, the small stumps would produce fast-growing sprouts. The only way to eliminate these plants is to kill their roots, but that requires uprooting the plants, which is a difficult and time-consuming operation that was rarely done.

An historical example of this situation is the intensive forest management treatments used for eastern white pine in New England from 1900–1930. White pine was a valuable species at that time for the production of boards to manufacture boxes and barrels. Most of it had established as "old-field pine" on pastures across New England in the 1850s. By the 1900s, the pines were merchantable. A second generation of white pine seedlings became established naturally after the mature pine stands were cut, but black, paper, and grey birch germinated at the same time. In addition, oak, chestnut, maple, ash, and other hardwood species had already become established in the understory. When they were released by the *de facto* overstory removals that were commonly done to harvest pine at that time, they quickly overtopped the new pine seedlings (one-cut shelterwoods would be the correct term if it had been purposely applied as a regeneration method). Machetes were used to cut the hardwood stems to provide growing space to the pine seedlings, but the hardwood sprouts could regain their previous height in one growing season after cutting. Cleaning operations were done

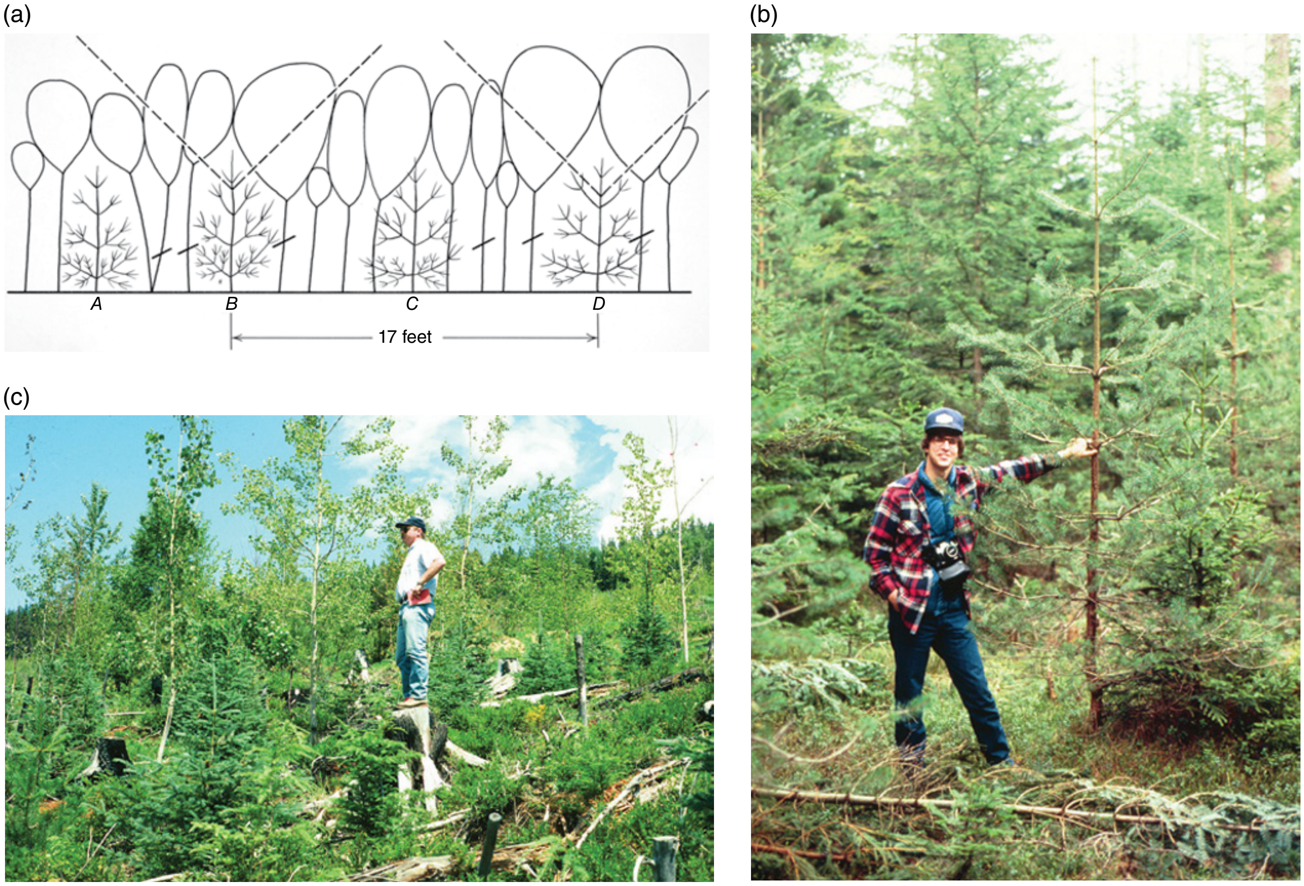


Figure 20.1 (a) A stand of conifer saplings being released as a cleaning from overtopping hardwood saplings and sprouts. In this example, trees B and D are being released by removing all hardwoods that project upward into an inverted cone with an apex just below the top whorl of the crop trees and has an angle of 90°. The competing trees to be removed are marked by slanted lines. This treatment would make trees B and D "free to grow". *Source*: Yale School of Forestry and Environmental Studies. (b) An example of a cleaning with a Scots pine sapling selected as the target crop tree, and the competing individuals removed that were overtopping it. *Source:* D. B. Kittredge, University of Massachusetts. Reproduced with permission from D. B. Kittredge. (c) A heavy cleaning release (free-to-grow) applied to a regenerating interior cedar–hemlock forest type in interior British Columbia, Canada. Only a few overtopping paper birch and aspen remain standing above a released understory of Douglas-fir, western hemlock, western redcedar, and western white pine. The heavy release is to affect the belowground competition for soil-water as much as the aboveground competition for light. *Source:* Mark S. Ashton.

repeatedly around selected pine, but in most cases only a small number succeeded in growing above the hardwoods. Only on sandy well-drained glacial outwash soils did pine out-compete hardwoods after cleaning operations (Hawley, 1922, 1927).

Vegetation Control Methods

In modern silviculture practice, the basic objectives of vegetation control are often the same as in past centuries, but a larger set of tools exists that makes it possible to kill both large and small competing plants, rather than to just temporarily reduce their growth. However, in some cases, a growth reduction is all that is required. These tools include herbicides (applied from helicopters, backpack sprayers, or tracked vehicles), brushsaws, chainsaws, and other mechanized cutting equipment. These methods will be described below, with some new experimental methods included as well.

Aerial Broadcast Application of Herbicides

The use of modern herbicides for forestry began in the late 1940s with broadcast spraying from aircraft. This method continues to be very important for the release of conifers in intensive management for single-species, single-aged tree plantations. Helicopters are generally used because they are much more accurate than airplanes at applying the herbicide (Fig. 20.2). Herbicide application is usually done in the early morning when winds are calm. The spray nozzles can be adjusted to control the droplet size, so that it is large enough to prevent drift off of the target area, but small enough to uniformly cover the vegetation foliage.

The main herbicide used for these aerial operations since the 1980s is **glyphosate** (see Chapter 18 on silvicultural

Figure 20.2 A helicopter with spraying operation in South Carolina. *Source:* Woodland Vegetation Management, Inc., Richlands, North Carolina. Reproduced with permission from Woodland Vegetation Management, Inc.

tools; Table 18.1), which is not selective in killing particular plant species. This presents a problem, because release operations consist of spraying herbicide over the site to selectively kill the hardwoods while leaving the conifers unaffected. The success of the aerial application method depends largely on two factors: (1) **differential wetting of foliage** which causes the herbicide solution to drip off of the narrow conifer needles, while coating the larger area of the broadleaf hardwood species; and (2) **different phenologies** timing of plant development, between conifers and hardwoods, which causes hardwoods with leaves to be susceptible to herbicides at a time when conifers are still dormant and not substantially affected by the herbicide.

The details of aerial herbicide applications are complicated (Talbert and Marshall, 2005; Fox, Jokela, and Allen, 2007; Fortier and Messier, 2006), but the general approach is as follows. The herbicide application method consists of a broadcast spray on the site early in the growing season, when leaves of the hardwood plants have already expanded and roots are actively growing, but the conifer buds are still dormant. A **surfactant** is mixed with the water and glyphosate solution to help coat the leaves, so that the solution does not bead up and roll off of the leaf surface. This gives more opportunity for the herbicide to move into the interior of the leaves¸ and then into the vascular system of the plant, and down to the roots. As the herbicide concentration increases to a critical level in the roots, the roots die, which then leads to the death of the entire plant. In some conditions, aerial application can also be done late in the growing season, after the newly produced conifer buds have become dormant, and the leaves of the hardwoods are still functioning. However, it cannot be applied in the middle of the growing season, because it would kill or injure both conifers and hardwoods.

Prior to the use of glyphosate, the same general method had been used for 30 years with the herbicide called **2,4,5-T**. However, that compound was banned from use in forestry and agriculture in 1979 in the US (and soon after in other countries), because it was discovered that a carcinogenic byproduct was created during the manufacturing process. There was then a period of several years when aerial spraying could not be done. It did not begin again until the details of glyphosate use were worked out. An even newer herbicide, **imazapyr** (see Chapter 18; Table 18.1), has a chemical structure that kills hardwood tissues, but does not affect conifers. Its use does not depend on the timing within the growing season to avoid damage to conifers. However, it usually is mixed with glyphosate for better overall control of a variety of competing species, so the method generally still follows the appropriate timing for glyphosate. The synergistic effect of mixing these two herbicides allows a lower total amount to be used to produce the same effective results.

Initially, only overtopping woody plants were seen as the species that reduced the growth of desirable seedlings. However, studies later found that the removal of herbaceous plants (grasses, ferns, forbs) resulted in a substantial increase in crop-tree seedling growth. The herbicides **hexazinone**, **sulfometron methyl**, and **imazapyr** could be used for killing herbaceous competition, including grasses (many older herbicides were not effective for killing grasses). By 1990, control of herbaceous weeds had become a widespread practice in plantation release (Lauer and Glover, 1998; Talbert and

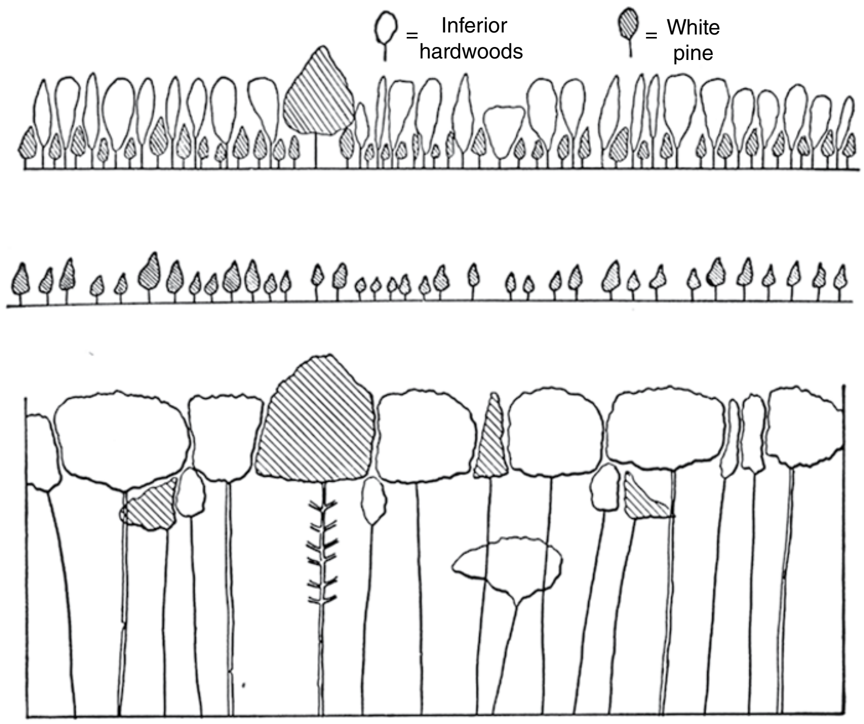


Figure 20.3 A schematic diagram depicting the effect of a weeding release treatment for planted conifers. The top illustration shows the current circumstance of pine overtopped by faster-growing hardwood competition and a larger poorly formed pine. The middle illustration depicts the successful release of white pine after weeding out the hardwood and the larger pine. The bottom illustration is what the young stand would look like if no weeding were done. *Source:* Yale School of Forestry and Environmental Studies.

Marshall, 2005; Fox, Jokela, and Allen, 2007). Part of the reason for focusing on herbaceous weeds was that site preparation was becoming more intensive, with the woody plants being eliminated before seedlings were planted. Release treatments were then used to eliminate the newly germinated herbaceous weeds at age 1 or 2 years after planting.

All of these broadcast herbicide treatments can be characterized as weeding. This is because they are largely indiscriminate of size class and species, and only select for conifers as target crop species. All other species are eliminated (Figs. 20.3, 20.4).

Ground-Based Application of Herbicides

The principal method of manually applying herbicide is with a backpack sprayer (Fig. 20.5a). This technology consists of a plastic tank that holds the herbicide solution connected to a spray nozzle that is controlled and aimed by the operator. The same herbicides can be used for spraying foliage on the ground as for aerial spraying. Foliar application can also be done with a mist-blower mounted on a skidder or similar forest vehicle, but the mist-blower cannot be aimed as accurately as a backpack sprayer. An important aspect of backpack spraying is that it allows for greater selectivity. It is possible to direct the herbicide spray on the foliage of the plants that are in competition with the crop-tree seedlings or saplings, avoiding both the crop trees and other vegetation that is not in direct competition with the crop trees. This is important for conserving the existing vegetation on the site. A plastic cylinder or other shield can be placed over the crop tree while the spray is directed on the surrounding plants. This can allow the treatment of competing plants that are very close to the crop tree. This practice is also especially useful if the crop trees are hardwood species. Protecting valuable hardwood saplings with shields may be the only way to use herbicide for releasing these trees, because the differential wetting and phenological differences do not apply in this case.

Ground-based spraying is more costly per unit of land area than aerial application, but it is becoming increasingly more common for a number of reasons. Aerial spraying has been banned in some jurisdictions, so ground-based spraying is the only choice in these situations. Also, silvicultural plans are including more partial harvesting (shelterwood, selection, patch cuts, and reserve-tree retention in various forms). These create regeneration areas that cannot be treated from the air. Application from the ground also diminishes the risk of herbicide drift, and reduces public concern about drift.

Other ground-based herbicide methods that do not involve application of herbicides on foliage are available. These methods focus the herbicide application on a more limited area. The **basal bark treatment** (or **basal spraying**) consists of applying an herbicide in oil in a wide ring around the lower part of the stem of a competing plant. This kills the dormant buds on the stem as well as the stem phloem and cambium, but it is only effective on small trees with smooth, thin bark. The **stump-surface treatment** (or **stump spraying**) is a method that involves cutting trees and immediately treating the

(a)

(b)

Figure 20.4 **(a)** A experimental treatment in Maine demonstrating the 3-year weeding release effect of herbicide (background) on killing blackberry, raspberry, and ferns (foreground) to release naturally regenerated spruce and fir after a one-cut shelterwood. *Source:* Mark S. Ashton. **(b)** A 4-year-old plantation of loblolly pine in Arkansas with a weeding release by broadcast foliar application of herbicide, killing hardwood brush and grasses. *Source:* Yale School of Forestry and Environmental Studies.

surface of the stump with a water solution of herbicide. The objective is the same as the basal spraying, but the herbicide diffuses down the vascular system to kill the stump and roots, thus eliminating sprout development. The selective applications of herbicide through the bark, on the stumps, or as a foliar spray around target trees, characterizes these kinds of release treatments as cleanings because only the competing vegetation around and over the target or crop trees is killed. Basal spraying or stump spraying can be very useful selective treatments to ensure post-establishment release of advance regeneration after shelterwood cuts, by removing competing

(c)

Figure 20.4 (Continued) **(c)** Released parts of a 15-year-old red pine plantation that had been established under oaks on a deep sandy soil in Michigan, 5 years after herbicidal treatment. *Source:* US Forest Service.

potential sprout growth of species like red maple, yellow-poplar, or sweetgum, or competing understory shrubs like rhododendron or kalmia (Groninger *et al.*, 1998; Kochenderfer *et al.*, 2001, 2004; Atwood, Fox, and Loftis, 2011). Treatments are also effective on the right site in releasing conifers from hardwood sprout growth, such as Douglas-fir from red alder in Oregon or Washington (Walstad *et al.*, 1986), and sugar maple from beech and red maple in Maine (Nelson and Wagner, 2011).

A third method is **soil application** (or **ground spraying**), which involves spraying herbicide on the ground at the base of competing vegetation so that plants take up the herbicide through their roots. The herbicide often used in this method is hexazinone, because it is so mobile. It kills the plants when the herbicide moves upward from the roots through the xylem to the leaves. However, it is difficult to be selective with this method. The herbicide is meant to be sprayed beneath the plants that are in direct competition with the crop trees, but if it is sprayed too close to the base of the crop-tree sapling, that sapling will also take up the herbicide. This will stunt its growth or kill it. A problem with all three of these methods is that each stem has to be treated, rather than spraying the canopy foliage of competing plants. This generally limits these applications to stands that have a low density of competing stems or only scattered patches of plants that need to be removed.

Manual and Mechanical Cutting

Manual cutting with brushsaws or similar equipment can be effective in controlling woody competition, especially when dealing with tall shrubs and understory trees. The reduction of shading by cutting overtopping vegetation is only temporary, because most hardwood trees and

(a)

(b)

Figure 20.5 Free-to-grow treatment. **(a)** A manual use of a backpack sprayer to control the invasive yellow star-thistle in Eldorado National Forest, California. *Source:* US Forest Service. **(b)** Brushsaw cleaning release operation of hardwoods around individual pines. *Source:* J. H. Miller, USDA Forest Service, Bugwood.org. Reproduced with permission from Bugwood.org.

shrubs produce sprouts from cut stumps. It may take repeated cuttings to allow the saplings to reach dominant positions above the competition. However, cutting has a high level of acceptance among the public, and it may be the only feasible method where herbicides are not allowed. Carrying out the cutting early in the growing season (but after leaf out has occurred) can help to reduce the number and vigor of new sprouts because carbohydrate reserves have already been used for shoot and leaf growth. Large tractor-driven equipment can be used to remove the competing vegetation between rows of seedlings in plantations. These generally have a large rotary cutting head with blades similar to a lawn mower. Some equipment has the cutting head mounted on a flexible boom. These are mainly useful when competing woody vegetation has become quite large. In that case, mechanical cutting removes the current vegetation, with subsequent herbicide application completing the vegetation

control. One of the limitations of this method is that the cutting head must avoid damage to the seedlings. A strip of vegetation next to the seedlings must be left uncut, and that is the vegetation that gives the most competition.

Although conifers are the focus of most vegetation control (Fig. 20.5b), cutting with brushsaws or chainsaws has an important role for **hardwood crop-tree release** through judicious cleanings. Generally, this consists of releasing hardwood saplings from other competing hardwoods. Some of the important crop species are paper birch and hybrid poplar in the boreal forest (Simard, Blenner-Hassett, and Cameron, 2004), oaks, maples, and cherry in the temperate forest (Heitzman and Nyland, 1991), and mahogany and teak in the tropics (Evans, 1992). Naturally regenerated hardwood stands are often very dense, and they are usually left in that condition in early stand growth to allow the shading to promote good stem form. However, the crop trees that are selected (based on species and stem form) can be released in order to allow them to grow into dominance. One variation of release cutting is to cut or break (by hand) the competing stems at about 5 ft (1.5 m) aboveground. The treated trees will stay alive, and will provide shading only in the lower part of the stem, helping to maintain the stem form of the crop tree. The crop tree will generally grow much taller than the broken competing saplings (Karlsson and Albrektson, 2001).

Cutting the stems of herbs, grasses, or ferns, two or more times within a single growing season may be useful to substantially reduce vegetation more than would occur with a single cut (Biring, Comeau, and Fielder, 2003). This **repeated-cutting method** is a kind of periodic weeding that works by reducing the stored carbohydrates in the roots. Timing is critical. The first cut is made just after the shoots have developed and the leaves are expanding. The plant will have invested a substantial part of its carbohydrate reserve in the new shoots and leaves, with little or no return yet from photosynthesis. When sprouts develop later in the growing season, they are cut soon after their leaves have developed. The cutting can continue in this fashion to kill the plants, but often only two cuttings will substantially reduce the competitive ability of the plant. This method has proven useful with large shrubs and ferns, many of them invasive, such as Japanese knotweed (*Fallopia japonica*), mugwort (*Artemesia vulgaris*), and hayscented fern (*Dennstaedtia punctilobula*) (Seiger and Merchant, 1997; de la Cretaz and Kelty, 1999). The problems involved with applying this method relate to cost and logistical feasibility, with a mowing protocol that cannot be too selective.

Other Techniques Used for Release Operations

Mulch mats can be used to suppress weed competition around planted seedlings (Thomas, Reid, and Comeau, 2001). These mats are made of polyethylene or other materials, and generally range in size 20–40 in^2 (50–100 cm^2). Mulch mats have been successful in suppressing weeds and accelerating height growth for Douglas-fir in Oregon and British Columbia (Harper, Comeau, and Bing, 2005) and longleaf pine in Georgia (Haywood, 2000). However, in other cases, it appears that either the roots of the tree seedlings grew beyond the edges of the mats, or weeds expanded their roots beneath the mats. In either case, the mats did not reduce competition after the first year (Harper, Comeau, and Bing, 2005). The cost of mats and associated labor makes this method rather expensive. This method might prove more applicable to urban conditions where planting stock and insuring individual tree survival are more critical.

Establishing **cover** crops on regeneration sites can serve to capture the open growing space that exists after site preparation and planting, and thus prevents weed competition from invading (Hartwig and Ammon, 2002). Cover crop species need to spread rapidly across the site, and they must have short stature and other traits that make them poor competitors of the crop trees. It is logical to use a legume species in order to add nitrogen to the site. A cover crop is not likely to prevent all weed growth, but it may be able to reduce the use of other vegetation control measures.

Grazing sheep in young forest stands can reduce competing vegetation, because sheep will eat grasses, ferns, and shrubs, but will generally avoid conifer tree seedlings. Grazing programs are complicated, and not all regeneration sites are appropriate. Ideal conditions are sites with a substantial amount of herbaceous vegetation, level or moderately sloping terrain, low amounts of slash, and few predators. Herds must be moved periodically to prevent damage to seedlings from overgrazing. In some cases, the sheep benefit from grazing the grasses and also reduce competing vegetation near the tree seedlings, but often there is no substantial negative effect on the growth of seedlings. The main use in recent years has been in British Columbia and the Pacific Northwest, but it has also become popular in the southern US, where sheep and goats, properly managed, can browse hardwood sprouts and grasses in newly planted pine stands. Sheep can also be managed to reduce the hardwood brush growth beneath pine, particularly if prescribed burning cannot be done (Popay and Field, 1996).

Timing and Extent of Release Treatments

High-Intensity Release Methods

With intensive high-yield plantation management, a substantial investment is made in planting stock, site preparation, and fertilization. It follows that competing

vegetation would be carefully controlled to protect that investment. The goal of the vegetation control is to maintain maximum growth rates of crop trees. This management approach has been used for plantations of loblolly pine and slash pine in the southeastern US, Douglas-fir and ponderosa pine in the western US and western Canada, red pine in the Lake States and central Canada, and spruce, fir, and pine species in Maine and eastern Canada (Wagner *et al.*, 2006). These release treatments increase stem volume production per unit land area in two ways. The first way is by improving survival of planted seedlings where substantial mortality may occur from dense overtopping woody vegetation. In those cases, stand-level stemwood volume may show 300–1000% increases over untreated stands. These large percentage increases do not occur because planted trees in the treated stands are three to ten times larger than those in the untreated stands. They occur because there are fewer planted trees in the untreated stands due to high mortality rates. The second way is when nearly all trees survive in both treated and untreated stands, but the treated stands have greater individual stem growth. These release treatments produce increases of 20–100% in planting seedlings over untreated stands. In either case, stand-level stemwood volume production is clearly increased substantially by the release treatments.

It may seem that to obtain maximum crop-tree growth rates, it would be necessary to eliminate all other vegetation from the site, but this is not true. The crop trees do not use all site resources, so there is no reason to spend additional money to remove all plants. The concept of the **critical period** of vegetation control has been adapted from agriculture (Wagner, 2000; Wagner and Robinson, 2006) to use in intensive forestry practice in order to determine the necessary treatment regime. The critical period starts when competing vegetation first begins to reduce maximum tree-seedling growth rate. It ends when vegetation-control treatments no longer increase growth. For a particular crop-tree species, this period is determined by establishing a large number of experimental plots with planted crop-tree seedlings. Ideally, all variations in the timing and number of years of herbicide application over 5 or more years would be included in these plots. Various studies have shown that treatments should begin in the first year after planting, and continue for 2–5 years, depending upon the growth rate of the tree species (Wagner, 2000). For example, fast-growing, intolerant jack pine has a critical period that extends from age 1–2 years. The period for red pine extends from age 1–3 years. The more shade-tolerant species of eastern white pine and black spruce have a period of 1–5 years. Douglas-fir, western hemlock, western redcedar, and grand fir all have critical periods of age 1–3 years, or 1–4 years. Note that all of these are annual applications. The end of the critical period for all of these species defines the time when the crop trees are free to grow. This is when they have taken over much of the growing space, to the extent that other vegetation no longer affects the growth of the crop trees. Most of the non-crop vegetation would just be low herbaceous species at that point.

Low-Intensity Release Methods

Many forest-management situations require much lower investments in silvicultural treatments. Plans for this low-intensity approach often call for only one release treatment. The objective is to maintain high survivorship of crop trees with good growth rates, but clearly not maximum growth rates. Crop-tree seedlings will compete with other species in the early years of stand growth, but will need to be released at some point to become free to grow. Timing is an important aspect when only one release is to be used. One possibility is to delay the treatment until the crop trees are tall enough that the regrowth of the treated existing vegetation will not be able to catch up and overtop the released saplings. However, periodic observations of stand conditions are needed in order to determine if it is necessary to act sooner than planned. Seedlings may become stalled in height growth or their survival may be threatened. It is important to recognize that some kinds of pioneer vegetation may look threatening, but will die off without causing significant harm. This is especially true of herbaceous annuals. The only plants that need to be eliminated are those that are going to substantially suppress the growth of the new stand. The reduction of undesirable vegetation should not be so great that even less desirable plants invade the growing space. It is a guiding principle of silviculture that no vegetation should be removed without having a good idea about what will fill the vacated growing space.

Delayed treatment is especially important for more shade-tolerant species, such as spruces, white pines, and true firs. These do not have fast height growth as seedlings even if they are in open conditions, but they are able to grow slowly with competition, and then later be released. Shade-intolerant conifer species, such as the hard pines, are more likely to respond with rapid growth if a vegetation treatment is applied in the first or second year. An important part of the timing decision needs to be based on the competitive conditions that site preparation created. If dense competition is present in the first year after planting, it may be necessary to use two treatments, with one very soon after establishment and then a second one several years later to release the tall saplings, in order to assure they will not be overtopped. The two-treatment approach may be more common when brushsaw cutting is the method in use.

One additional aspect arises when crop trees have been established as natural regeneration. There are usually far

more seedlings than needed in order to produce a fully stocked stand. Thus, release treatment operations include selecting the best crop trees, based on both tree quality and predetermined spacing, and then releasing only those crop trees. It is generally sufficient to release 150–300 trees/acre (375–750 trees/ha) to provide for both the final crop and one thinning, as well as a margin for losses.

Ecological Impact of Release Treatments on Plant Communities

This chapter so far has been focused on the suppression or elimination of the vegetation that competes with crop-tree seedlings and saplings. However, that competing vegetation is of considerable importance for its conservation value. It constitutes the native plant community of the area, and provides the habitat structure for wildlife. Increasingly, non-native plant species have also become a part of the plant community. It may seem that nearly all vegetation (except the crop trees) is eliminated in intensive weeding treatments. In fact, plant communities persist and recover after treatments. However, the rate and diversity of species recovery depend on the type and number of treatments (Miller *et al.*, 2003a, 2003b) (see Box 20.1).

The term **plant diversity** is often used as the goal for conservation of plant communities. High diversity usually just means a large number of plant species. A more technical use of the term is associated with the **species diversity index measurement**. However, that measurement turns out not to be very useful in assessing plant communities in these management situations. The more useful measures are **species richness** (the total number of species present), and **relative species dominance**

Box 20.1 A comparison of the effects of alternative release treatments on planted conifer crop-trees and native vegetation.

The principal use of release treatments is to release planted conifer seedlings and saplings from competing vegetation. There is increasing interest in using methods that allow a range of vegetation components to survive and persist. This example of release treatments is based on data from a study of black spruce plantations in Ontario (Pitt, Wagner, and Towill, 2004), and presents a comparison of the differences among the most common release treatments (described earlier in this chapter). Quantitative comparisons can be made from the mean cover percent and mean heights of conifers and the other vegetation components, at age 10 years after planting (Fig. 1).

The stand in this study had been clearcut with a whole-tree harvest. Mechanical site preparation was done with a disk trencher to create furrows. No chemical site preparation was used. Bare-root black spruce seedlings were planted at 7–10 ft (2.2–3.0 m) spacing, on the tops of the furrows. The plots in all four treatments were treated the same way in the site preparation and planting.

The **untreated stand** was planted with black spruce seedlings, but with no release treatments. At age 10 in the untreated stand, the planted spruce were overtopped by trees and tall shrubs. Mean heights of poplar trees were 13–18 ft (4.0–5.5 m), with the conifer crop trees in this stand having heights of only 8 ft (2.5 m). The crop trees were completely overtopped, with a cover of only 30% in the stand. The full range of vegetation components was present, from grasses to trees.

The **repeated foliar herbicide application method** (annual removal) was the most intensive release method. It consisted of glyphosate application on the foliage of the site each year for 5 years, which has been shown to allow maximum conifer growth rates. This was done from the ground but it simulated the effects of repeated aerial foliar application. The intensive method of 5 years of foliar herbicide application produced crop trees with 70% cover and nearly 13 ft (4 m) tall. The non-crop vegetation was made up almost entirely of grasses and forbs; other components were rare or absent.

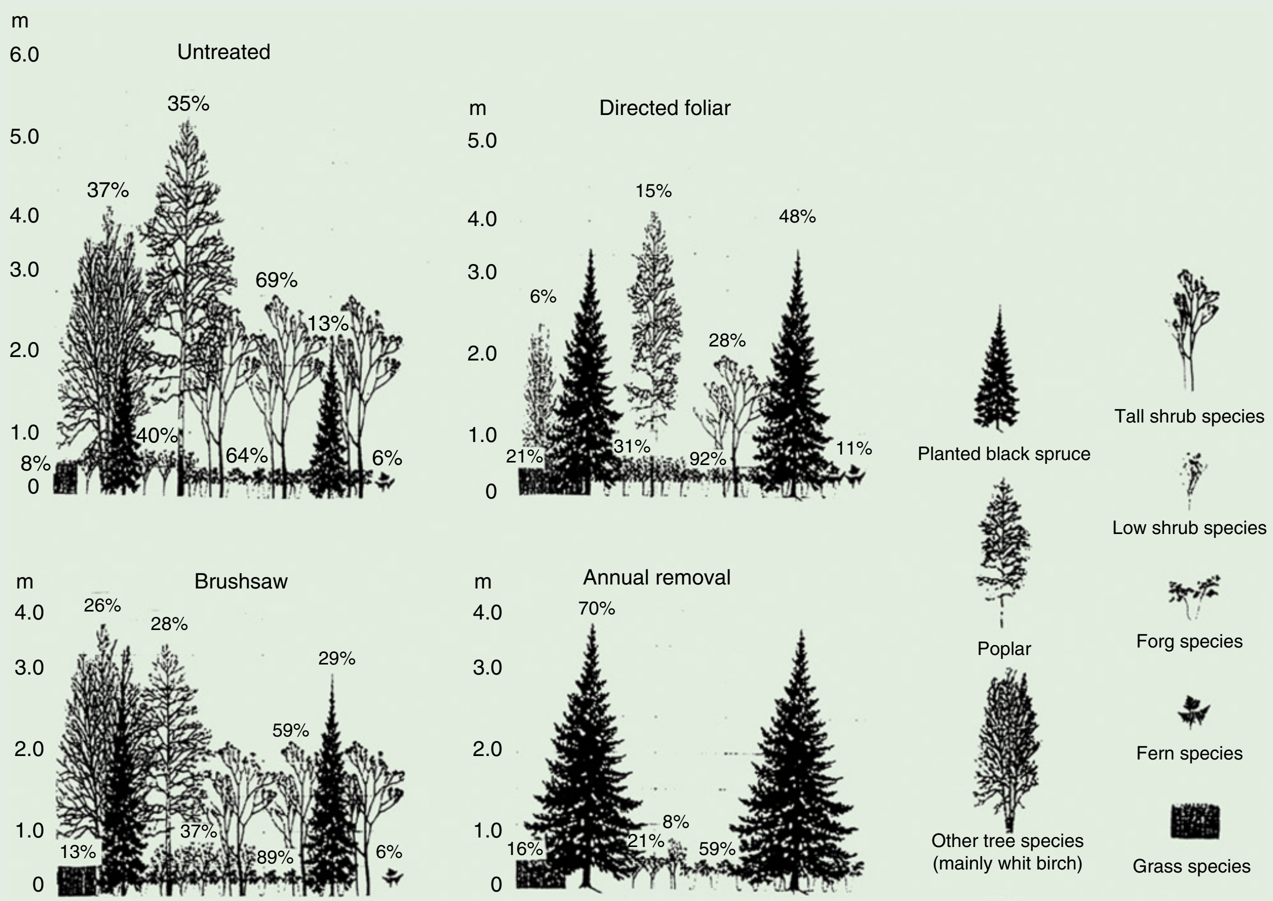
The **directed foliar application method** simulated a backpack-spraying application. The glyphosate herbicide was sprayed on foliage of all vegetation within a 3-ft (1-m) radius of each crop tree (with no herbicide application on the crop tree itself or on vegetation farther than 3 ft away from a crop tree). The single application of directed foliar herbicide produced free-to-grow crop trees with heights of 12 ft (3.5 m). This was just slightly shorter than crop trees in the intensive method, but with less cover (50%). Vegetation was similar to the untreated stand in having a range of vegetation components, but all components had reduced cover compared to the untreated condition.

The **brushsaw cutting method** was used to cut all woody stems within a 3-ft (1-m) radius of the crop tree. The single treatment using a brushsaw produced competing vegetation that was denser than that in the single herbicide application method, likely because of the resprouting that occurred after cutting. Conifer crop trees in these two stands also had the same height, but the greater vegetation density reduced the conifer growth in cover to 30%. It is not clear if all or most of the crop trees in the stand that had been cut will be able to outgrow the hardwood trees; a second cut may be needed to release them from becoming overtopped.

Source: Adapted from Pitt *et al*., 2004.

(*Continued*)

Box 20.1 (Continued)



Box 20.1 Figure 1 An illustrated comparison of the effects of alternative release treatments on planted conifer crop-trees and native vegetation. Top left – untreated control; top right – a one-time directed foliar herbicide application; bottom left – brushsaw treatment; bottom right – annual removal through foliar herbicide treatment for 5 years. *Source:* Adapted from Pitt *et al*., 2004.

(the ranking of species from common to rare). The dominance rank of a species is determined by using **cover percent** (the percent of the land area that is covered by the foliage of each species). With dominance and cover percent, it may also be useful to divide the native and non-native species.

Most untreated plant communities have only one or a few species that dominate a site, with the other species being much less common. The main effect of an herbicide treatment is that the dominant species are reduced substantially in cover percent. This creates empty growing space that is soon filled by a variety of species including, of course, the crop trees. This generally leads to an increase in species richness, with more evenness among plant species (that is, many plant species, each with a moderate cover percent). Nearly all of the species would have been on the site before the treatment, and they recover by re-colonization from existing root stocks and by germination from the seed bank. Most are native species, but non-native species may invade as well. When release treatments have been completed, herbaceous species recover first. Then, as the tree canopy begins to close, shading reduces herbaceous species. Hardwood trees and shrubs may increase in size, but often they do not increase in numbers from new establishment, because forest floor conditions are generally not suitable for germination. However, shrub and tree species that have clonal growth may expand across the site (Pitt, Wagner, and Towill, 2004).

Intensively treated stands may have high species richness, but the actual cover represented by the five vegetation components described at the beginning of this chapter, is greatly reduced. With less intensive vegetation-control treatments, such as directed spray or brushsaw cutting, the same patterns will likely exist, but greater amounts of all vegetation components will likely be present.

It should be remembered that the measures of plant species richness and dominance do not give any information about which species are present on a site. A forest that has not been harvested for many decades will often have lower species richness than nearby stands that have been recently harvested. However, many of the species in the uncut stand will not be found in cut-over stands. These would likely include shade-tolerant understory vegetation and species of mosses, lichens, and epiphytic plants that tend to be rare. This situation calls for maintaining patches or stands of unharvested forest within a managed forest landscape for those species that are generally found in undisturbed forests and are slower to colonize new areas.

Liberation Treatments

Liberation, in the silvicultural sense, refers to the release of young stands from the competition of distinctly older, overtopping trees. This kind of operation is needed when regeneration becomes established beneath a partial overstory canopy that is too dense (Fig. 20.6). This often results from poor management practices, such as high-grading. Other cases start with good intentions but end with poor results. For example when a stand is thinned too heavily it can create an overstory that will later be damaged by wind.

Figure 20.6 A stand of loblolly and shortleaf pine in Louisiana, approximately 5 years after liberation girdling of an overstory of oak. Most of the young pines were small seedlings at time of release. *Source:* US Forest Service.

Liberation cuttings to even-aged stands are some of the first release treatments that can be applied after successful establishment of natural regeneration through irregular shelterwood or seed-tree methods. Where too many structural reserves have been left, such that now they are impeding the growth of the new stand, liberation needs to be done.

Liberation treatments are the only precommercial release cuttings that are done together with the selection regeneration method. Where large trees are being purposely felled to create new open growing space to establish new regeneration or release advance growth, other areas of the stand usually need liberation treatments to release saplings and poles. These areas of the stand established regeneration from prior entries and that are now overtopped and impeded by in-growth from the surrounding older canopy trees (Ohlson-Kiehn, Pariona, and Frederickson, 2006; Peña-Claros *et al.*, 2008; Jonkers and Hendrison, 2011) (Fig. 20.7a). Liberation cutting is needed to push back the edge effect of the larger, older trees surrounding the regeneration established in the old openings.

In the case of diameter-limit logging or high-grading, the trees removed in liberation operations are not the result of planned silviculture. In this case, there is often a moderate to high density of mid-canopy trees, usually with small crowns and poorly formed stems. In other cases, there may be a small number of widely spaced large trees with spreading crowns and poorly formed stems. In both situations, liberation treatments can be used to release an age class of younger seedlings, saplings, or poles.

Liberation treatments can also be used to remove overstory trees in restoration enrichment plantings within heavily logged-over forests where the in-growth from the canopy has shaded the plantings (Kuusipalo *et al.*, 1997; Schwartz *et al.*, 2013) (Fig. 20.7b). In other circumstances, a major element of canopy shade, particularly in selectively logged forests, is vine growth across the canopy. Liberation cutting is a useful tool to eliminate the vines (Peña-Claros, *et al.*, 2008).

When considering a liberation treatment, there are a number of decisions to be made, largely based on current stand conditions. If the overstory trees are widely scattered and the regeneration has value for a future stand, a liberation removal of those trees may not be warranted. These overstory trees could just be left as reserves, allowing the understory to grow up around those older trees. However, if the seedlings or saplings have low stocking or are of predominantly undesirable species, it may be better to start over, using site preparation and treating the overstory as needed for the regeneration plan. The ideal

(a)

(b)

Figure 20.7 **(a)** Liberation treatment using stem injection of herbicide to release saplings beneath older overtopping non-commercial trees. *Source:* James H. Miller, USDA Forest Service, Bugwood.org. Reproduced with permission from Bugwood.org. **(b)** Liberation release along an enrichment line planting of timber trees within a selectively logged mixed dipterocarp forest in Malaysia. *Source:* Mark S. Ashton.

situation is if the overstory trees have enough merchantable value (likely only pulp or biomass chips) to pay for the costs of the overstory removal. In many cases of liberation, killing the overstory trees in place, would be the most efficient option through mechanical girdling (triple chainsaw cuts) or chemical girdling (herbicide injection into spaced ax cuts) (see Chapter 18 for details). In most cases, minimal investment is used to rehabilitate a poor stand condition. If bad management has accidentally produced excellent regeneration in a stand, there is no reason to not invest in other treatments along with the liberation cutting. One example is releasing the saplings from competing understory vegetation through cleanings.

Release Treatments that Control Invasives

Finally, treatments that have been developed in forestry to promote the release of regeneration from forb, grass, and shrub competition are widely applicable to controlling invasives, many of them exotic and widespread in disturbed landscapes (Table 20.1)

Table 20.1 A list of exotic plant invasives by region within the US and their control.

Species name	Common name	Growth habit and area of naturalization	Mode of control
Alliaria petiolata	Garlic mustard	Northeastern and north central states. Originally from Eurasia. A biennial that was used as a vegetable during colonial times. Shade-tolerant of forest understories to roadsides	Prescribed burning is effective, cutting all tall individuals that will flower with a sickle or scythe and taking cut stems off site. Repeated treatments necessary
Berberis thunbergii	Japanese barberry	A shrub originally planted as an ornamental from Japan. Found mostly in the northeast. A shade-tolerant of the understory. Bird dispersed	Large patches can be controlled by burning with follow-up spot foliar application of Roundup when it re-sprouts, or broadcast foliar application of Roundup for dense patches. Cut stumps can be applied with Garlon
Bromus tectorum	Cheatgrass	Widespread annual winter grass on open woodlands, rangelands, roadsides, and agricultural lands. Originally from Eurasia. Dispersed by animals. Viable in the soil for up to 2–3 years	Foliar applications applied in early spring. Repeated for several years. Careful monitoring needed continuously
Calastrus orbiculatus	Bittersweet	Throughout forests of the eastern US. A liana that requires edge and forest fragmentation to gain control. Dispersed by birds	The best control is cut-surface treatment using Roundup of fully leafed-out plants
Cirsium arvense	Canada thistle	Sun-loving herbaceous colonizer of disturbed soils. Dispersed by wind and stored as buried seed. Widespread	Grazing by goats, targeted foliar application of Roundup. Repeat follow-up visits required
Cytisus scoparius	Scots broom	Native of Europe. A leguminous shrub found in eastern and western US	The best mode of control is by application of Roundup or Accord to the cut stump
Eleagnua umbellate	Autumn olive	Sun-loving small tree/shrub that colonizes open areas. Bird dispersed. Eastern North America	Brushcutting in the fall and applying Chopper, Garlon, Roundup, or Tordon as labeled to the cut surface immediately afterwards
Euphorbia esula	Leafy spurge	Distributed widely across the northern half of the US. Invades open area and roadsides. Especially competitive on dry sites	Apply foliar application of herbicide (Plateau, Streamline) in fall
Fallopia japonica	Japanese knotweed	Throughout the northeastern US. Clonal understory herbaceous shrub, particularly in moist areas and along waterways	The most effective control is to cut it back in mid-growing season, let it sprout and then apply foliar application of Roundup The root systems are extensive and so this may need to be done for several growing seasons. The use of Arsenal is more effective but it has much greater and persistent legacy effects in the soil for non-target species

(*Continued*)

Table 20.1 (Continued)

Species name	Common name	Growth habit and area of naturalization	Mode of control
Lygodium japonicum	Japanese climbing fern	Found across the southeast in forest understories. Spores travel by wind and form clonal rhizomous root systems	A foliar application of Roundup or Escort has proven effective
Microstegium vinimium	Japanese stiltgrass	Throughout the eastern US. An annual that is dispersed by animals and people. Colonizes roadsides and spreads to forest understories. Shade tolerant	Small populations can be hand pulled before seed set. Foliar applications can be done using Roundup (or Rodeo in wetland situations)
Pueraria Montana	Kudzu	Found throughout the southeast. An escape from northeast Asia. A liana that is both a dense ground cover and smothers trees	Repeated grazing by livestock over a number of years followed by spot herbicide to finish off degraded plants using Roundup as a foliar application
Rhamnus carthatica	Common buckthorn	Central and northeastern US. Shade-tolerant small tree from Eurasia. Dispersed by birds	Brush cutting and applying Roundup immediately to the cut surface
Rosa multiflora	Rosa multiflora	Widespread across the US. A scandent shrub found in open grasslands and old fields. Bird dispersed	Control is best with spot foliar application of the herbicide Cimmaron. Cut stump and basal stem sprays can be applied with Pathfinder II
Shinus terebinthifolius	Brazilian peppertree	Sun-loving shrub and small tree of open areas. Restricted to Hawaii, Florida, and southern California. Bird dispersed	Brush cutting and applying Roundup immediately to the cut surface. Basal oil-based bark spray application using Garlon or Pathfinder
Tamarix spp.	Saltcedar	A tree distributed across the western US, particularly along waterways and riparian zones	Apply basal spray using diesel fuel with the herbicide Remedy during the growing season

Source: Mark S. Ashton.

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21

Methods of Thinning

Introduction

The thinning of forest stands by removing individual trees or groups of trees is done to create new growing space, with the main purpose of producing larger trees for timber production or for sap/latex production from the stems. Thinning can also be used for producing stand structures that create viewsheds, increased water availability, forest health, or fire protection. There are a number of thinning methods that are described in this chapter. However, it is important to recognize that it is best not to use thinning if the focus is to maximize biomass for carbon sequestration, fuelwood production, pulp, or some product that does not require large-dimension trees. In that case, trees should be densely packed and occupy growing space as quickly as possible after their establishment, so as to maximize yield per unit space, and no emphasis should be placed on individual tree health. Also, thinning is not used in agroforestry cropping systems, orchards, or urban environments; these trees are usually planted at wide spacing to maximize their individual health, growth, yield, and form.

Thinning is a compromise between the two extremes of (1) maximum growing space per land area, such as producing a dense fuelwood stand, and (2) maximum growing space per individual tree, such as producing fruit orchards, starting with an open stand and gradually growing into a nearly closed stand. Forest thinning removes designated trees to partially open a dense stand to give greater growing space for specific trees. It is usually good to keep thinnings light enough to restrict the growth of any shrubs, vines, or undesirable trees that will cause problems at the time of regeneration. The gaps created in the crown canopy by most thinnings are so small that they close before any understory trees can start the kind of rapid, sustained growth in height necessary to count as new age classes of regeneration. Thinning is done to regulate the distribution of growing space for the benefit of the existing stand and not to vacate enough space to start a new one. Attempts, either ambitious or casual, to obtain regeneration and secure the benefits of thinning simultaneously often result in doing neither thing well. Desirable regeneration may appear under stands as a result of thinning or even without any treatment. If it is persistent enough or is deliberately sought, then it is advance growth, and it is best regarded as part of the start of the shelterwood regeneration method rather than as a result of what was intended as thinning. This semantic switch helps focus attention on the source and nature of the regeneration process, which is a more crucial step in the silvicultural system than thinning.

This chapter describes six different approaches to thinning that can be characterized in order as low, crown, dominant, free-form, variable density, and geometric. For each kind of thinning, the principle approach is described, and examples of both suitable application and misuse are provided. The last part of this chapter describes how thinnings are applied as a schedule over time.

The Different Approaches to Thinning

When dealing with thinning, it is first important to understand that a key aspect of forest development is the natural process of stand differentiation, in which competition among trees leads to variation in tree sizes. For a single-aged, single-species stand, this usually leads to the death of the smallest trees in the overtopped and intermediate crown classes. For mixed-species stands, shade-tolerant species can withstand being overtopped and will eventually become the canopy in time. Generally, a small number of dominant and codominant trees die, caused not by competition, but from lightning, wind, insects, or disease. However, when foresters are thinning stands, they make choices about which trees are to be removed and which are to be left alive, and these choices may either match or counteract the natural patterns of stand development.

Thinnings can be defined as **the judicious removal of trees to reallocate growing space to other trees and plants. Thinnings are made to individual trees and stands that are considered beyond the release stage**

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

of treatment (i.e., beyond seedlings, saplings, and pole-stage stands). Many thinnings are carried out for timber management, either to salvage small trees in order to increase total yield of wood from a stand, or to increase the growth rates of selected crop trees. Other thinnings are designed to create particular forest structures in order to improve wildlife habitat conditions, produce certain landscape aesthetic characteristics, reallocate growing space to the groundstory in a mixed tree-crop system, or to reduce the risk of fire. In many situations, multiple objectives are involved in the design of a thinning operation. Some of these thinnings will be **commercial thinnings** that produce a net income from the trees that are cut. Others are **precommercial thinnings** that are carried out as investments, in which the costs of thinning operations exceed any income from the cut. These are conducted to improve the stand in terms of tree health, growth rate, or stand structure for the future.

Six main methods have been developed to aid decision making about which trees are to be retained and which are to be removed when a stand is being thinned. These methods are: (1) **low thinning**, (2) **crown thinning**, (3) **dominant thinning**, (4) **free-form thinning**, (5) **variable-density thinning**, and (6) **geometric (or mechanical) thinning**. In the first three methods, the choices are based mainly on the position of trees within the crown canopy structure. Free-form thinning is the thinning method that consists simply of a combination or modification of any of the first three methods, applied in a single thinning operation. Variable-density thinning creates an intentionally irregular pattern of tree spacing to create complex stand structures and habitats. Geometric or mechanical thinning deals with the spacing pattern of trees in the stand as the principal consideration. Each of these six methods will be considered in detail in this chapter.

Thinning methods tend to be associated mainly with even-aged stands, but the principles of these methods can also be applied to even-aged forest patches within multi-aged stands. In fact, thinning is an important part of the management of nearly all multi-aged stands, but is often overlooked in all-aged stands particularly when using the selection method and its focus on a combination of regeneration, release, and thinning together.

Low Thinning

The low thinning method (also called **thinning from below**) is the oldest, having been the standard approach used in early forest management in central Europe (Zeide, 2001; Puettmann, Coates, and Messier, 2008). In low thinning, trees are removed from the understory and other lower crown classes, and the removals can progress further into the higher crown classes, depending upon the intensity of thinning. This mimics the natural mortality that occurs in self-thinning within single-aged, single-species stands, but it accelerates the process. A traditional system for identifying thinning intensity in the low thinning method uses four grades (A, B, C, D), which range from A for a very light thinning to D for a very heavy thinning (Fig. 21.1). In A-grade low thinning, only overtopped trees are removed; this often includes only the trees that are nearly dead due to suppression from larger trees, but the canopy remains unbroken. In B-grade low thinnings, the intermediate crown class is also eliminated, along with the overtopped trees. The main virtue of A- and B-grade thinnings is that they salvage the smaller trees to use for fuelwood or other products for which small-diameter material can be used. These trees have done most of their growing already and will either die soon or merely survive without much further growth.

Because the object of many thinnings is to increase the growth rate of the remaining trees (and not merely salvage dying trees), the heavier C and D grades of low thinning are more commonly applied than the light A and B grades. Both of the heavier grades involve deliberate creation of temporary canopy gaps in order to accelerate crown expansion of the remaining trees (Fig. 21.2). In the C-grade thinning, some codominants are cut along with the lower crown classes; in the D-grade, many but not all codominants are cut. The use of low thinning does not imply that no main canopy trees are cut, but that, if main canopy trees are cut, then all smaller, intermediate and overtopped trees are also cut. The principles of these four grades are still used, but thinning intensity is now generally determined by a quantitative measure, such as the percent of stand basal area that is cut, relative to the initial stand basal area, or as determined by a target residual basal area.

Low thinning has a logical relationship to the natural course of stand development. It is easy to pick the trees to remove; those that remain are likely to continue the rapid growth that has already put them in the upper crown classes. However, the removals are concentrated in the small trees that are least likely to be marketable. Low thinnings have to be very heavy, or else be repeated frequently, in order to create enough open growing space for the larger trees to expand their crowns significantly (Fig. 21.3).

The low thinning method was developed several centuries ago, where small trees and even branches were used for fuelwood, fenceposts, tool handles, and other similar products. In general, there are fewer uses for these small trees at present, and there is a tendency to just leave them in stands. Where there is little use for small trees, low thinning can be delayed to the later stages of the rotation after the trees have become

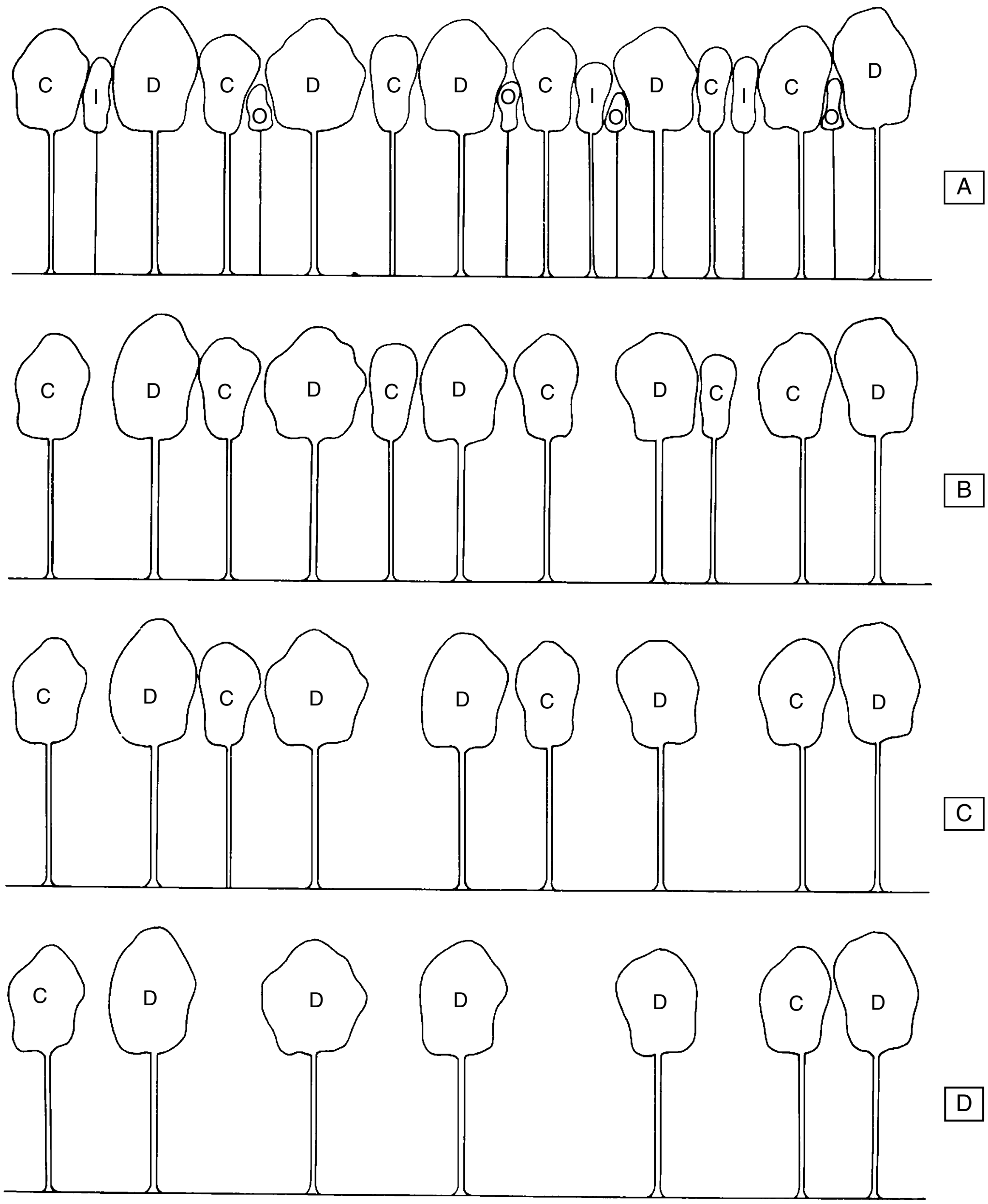


Figure 21.1 The B, C, and D grades of low thinning as they might look if each were applied in the same unthinned, even-aged stand (top). The letters on the crowns denote crown classes and the letters at the right denote the grades of low thinning. The rarely used A grade (removal of overtopped and dead trees) is omitted. In current practice, basal area is used rather than the grades (A, B, C, D) for determining intensity of low thinning. *Source:* Yale School of Forestry and Environmental Studies.

merchantable. Small or poor-quality trees can be chipped for pulp or biomass use, if appropriate harvesting equipment is available to move in a stand without damaging the larger crop trees.

Other purposes for removing these trees (even when small), include "lifting" the level of the canopy foliage so that better views of the landscape can be seen beneath the canopy. The reduced amount of tree foliage will usually promote new understory vegetation which will affect habitat conditions for wildlife, such as increasing mast crops from trees with larger crowns. In some regions, the removal of small trees in low thinnings is critical for reducing the risk of fire.

Low thinnings are most obviously applied to even-aged stands of single species either in natural regeneration or in plantations. Applying thinnings from below does little to change species composition or successional position of the individuals that are growing best. However, applying low thinnings uniformly to mixtures of tree species that grow at different rates can be very

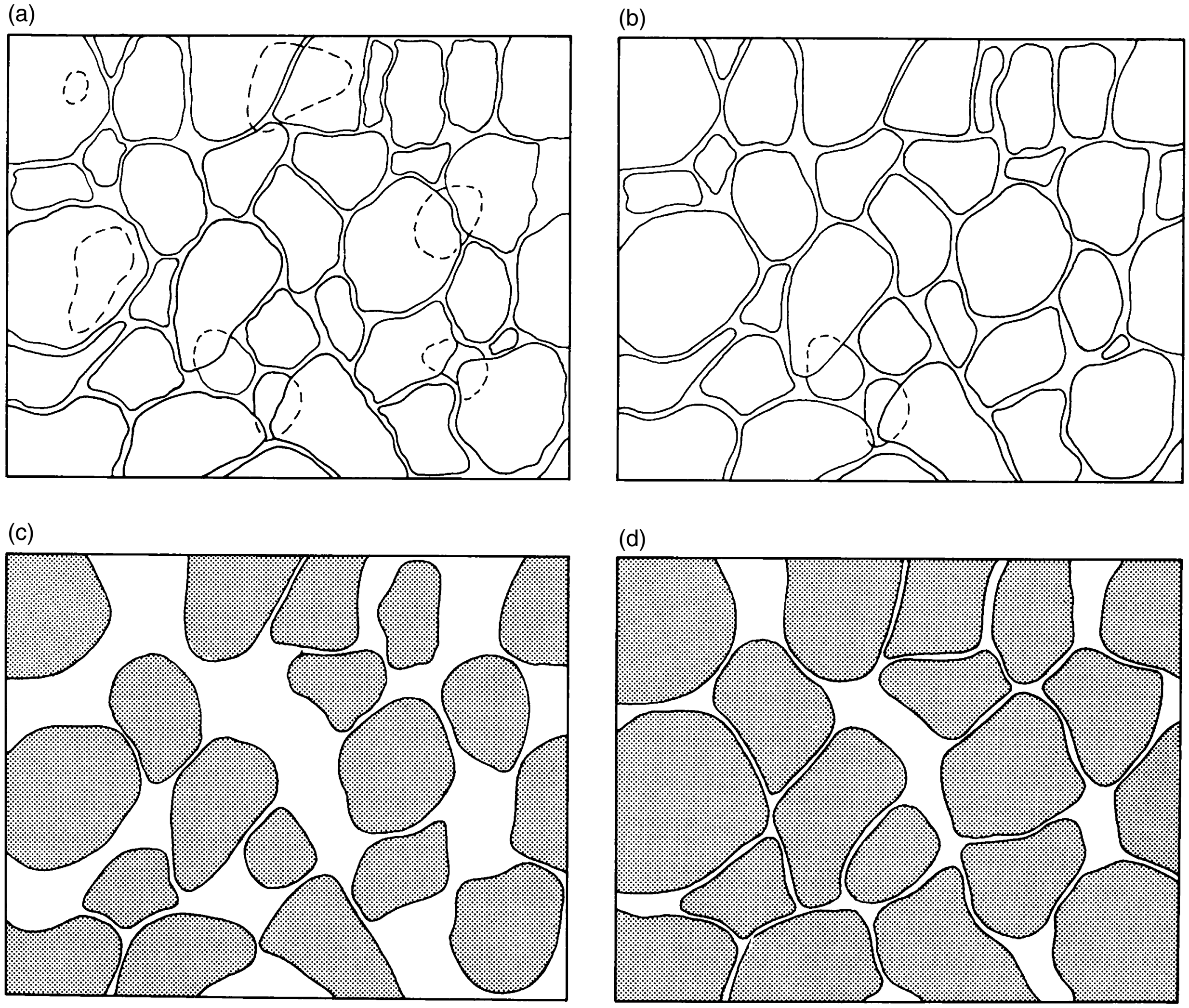


Figure 21.2 The effects of the lightest and heaviest intensities of low thinning, as viewed from above. The even-aged unthinned stand (a) shows crowns with solid lines for upper canopy trees and dashed lines for the portions of crowns that are overtopped. The A-grade thinning, shown in illustration (b), leaves the canopy unbroken. The D-grade thinning (c) has left only dominants and some codominants with each tree released from crown competition on one or more sides; the same stand 10 years after the D-grade thinning (d) with the canopy nearly closed. *Source:* (a–d)Yale School of Forestry and Environmental Studies.

detrimental. In these circumstances, applying low thinnings would remove the smaller trees that are not necessarily of poor quality or health. The tree species that are usually slower growing and more shade tolerant likely represent the future late-successional forest canopy. Even in mature forests where these shade-tolerant trees have ascended into the canopy, the understory can represent shrub and small treelet growth habits that will always remain in the understory. Applying a low thinning would eliminate many species but not necessarily improve growth, particularly in drought-prone forests (Kelty, Gould, and Twery, 1987).

Apart from the regular application of low thinnings to single-species plantations and naturally regenerated stands where markets exist for small-dimension timbers, there are many other examples where low thinnings are currently applied. The most obvious example is in the western US, where the term **restoration thinning** is used (Covington *et al.*, 1997; Brown, Agee, and Franklin, 2004). Much of this is essentially heavy low thinning applied to even-aged stands of shade-intolerant conifers, such as lodgepole pine and ponderosa pine (Feeney *et al.*, 1998; Finkral and Evans, 2008). Other treatments besides thinnings are also used within the "restoration" methods in this area. Because of fire suppression in these stands, more shade-tolerant species such as white fir and Douglas-fir establish below the shade of the intolerant pines. This can pose a catastrophic fire-risk due to the increased chance of intense crown fires that move quickly when there are ladder fuels from the understory,

Figure 21.3 A plantation of eastern white pine at Biltmore, North Carolina, during a series of five low thinnings. The first thinning was at age 20, and later thinnings were made at intervals of about 6 years, reducing the basal area to 100 ft^2/acre (435 m^2/ha) each time. **(a)** Unthinned stand at age 20, with numbered trees to be left in the first thinning. **(b)** Stand at age 26, with numbered trees to be left in the second thinning. **(c)** Stand at age 32. **(d)** Stand at age 45, just after the fifth thinning. *Source:* **(a–d)** US Forest Service.

where dead and dying timber from severe competition for moisture and light can occur, especially during dry years. One solution is to remove all smaller stems of fir, opening up the stand from below to encourage growth of the canopy. This removes belowground root competition for water, increasing soil water availability and increasing the vigor and health of the remaining canopy trees (North, Innes, and Zald, 2007). This is especially applicable to where fire-prone forests with dense understories interface with the suburbs (Kalbokidis and Omi, 1998) (see Box 21.1).

Low thinnings can be appropriately applied to encourage pasture grasses beneath canopies of trees in silvo-pastoral systems, or for increasing soil moisture and light for cultivation of shrubs and herbs for food, medicine, or horticulture (Fig. 21.4), or for increasing herbaceous diversity

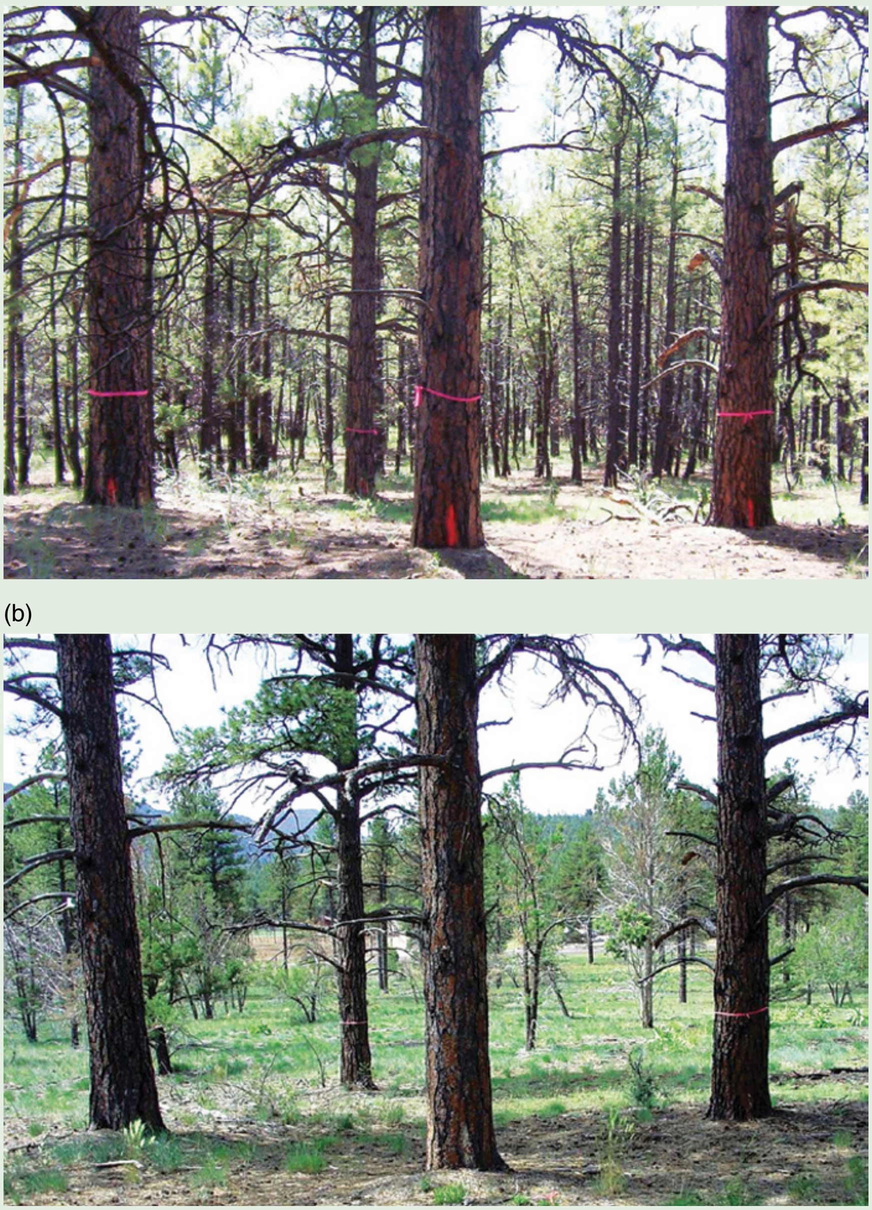
(Thomas *et al.*, 1999). Low thinnings can be applied to stands to increase below-canopy viewsheds along trails, roads, and urban parks (Thompson *et al.*, 1999).

Examples of where low thinnings should be practiced with great caution are where forests are mixed and stratified. Usually this includes temperate moist and tropical moist forests. People have a tendency to harvest small-diameter fuelwood or to cultivate **non-timber forest products** (**NTFPs**) (e.g., shade coffee, shade tea, cacao, cardamom, gingers) in these topical and temperate moist forests, and they do this by removing the understory (Tscharntke *et al.*, 2001; DaMatta, 2004). This can

Box 21.1 Applying restoration thinnings in the western US.

(a)

(b)



Box 21.1 Figure 1 Before **(a)** and after **(b)** photographs of an overstocked ponderosa pine stand that had been given fire protection for the last 50 years in the Coconino National Forest, Flagstaff, Arizona. The four large original pine trees in the foreground were the seed source for younger individuals that established mostly in the 1920s after a favorable period in climate and masting. The treatment can be regarded as a very heavy low thinning that removed almost all the smaller trees relatively uniformly across the stand. *Source:* **(a, b)** Grand Canyon Trust. Reproduced with permission from Grand Canyon Trust.

Box 21.1 (Continued)

Box 21.1 Figure 2 A photograph of the restoration thinning treatment being carried out. To reduce the danger of future wildfire, the small-diameter pine trees that are removed are chipped and scattered on the ground, or if the chips are merchantable, they are sold as a wood fuel. An alternative is to remove what is merchantable and then pile the slash, and allow it to sit over winter, to be burned in the early spring when the snow is still on the ground to prevent any possibility of fire. *Source:* US Forest Service.

(a) (b)

Figure 21.4 Photographs of low thinnings. **(a)** A silvopastoral system with an overstory of black locust, a nitrogen-fixing leguminous tree in upstate New York. *Source:* B. Chezdoy, Cornell Cooperative Extension. Reproduced with permission from B. Chezdoy. **(b)** The cultivation of ginseng, a non-timber forest product. *Source:* USDA National Agroforestry Center.

eliminate both the true understory stratum of shrubs and small tree species, as well as the slower-growing, late-successional trees of the future forest canopy (Dhakal *et al.*, 2012). Such treatments can dramatically reduce the species richness of a forest, reduce the stratification by removing the subcanopy, and eliminate the ability to establish advance growth of late-successional trees at a later time with the loss of their seed source. The only alternative for later growth of these late-successional species, once they have been removed, is to plant (Fig. 21.5).

(a)

(b)

Figure 21.5 **(a)** A photograph of a heavy low thinning that has been inappropriately applied for fuelwood cutting in a temperate mixed maple-oak–pine forest in New England. It has removed much of the slower-growing shade-tolerant subcanopy species and has resulted in the uniform establishment and release of black birch and red maple. **(b)** A heavy low thinning in an old-field eastern white pine stand removing all overtopped, intermediate and codominant white pine for saw timber and pulp to favor the best white pine dominant and codominants. *Source:* **(a, b)** Mark S. Ashton.

Crown Thinning

The crown-thinning method (also called **thinning from the middle**) overcomes some of the limitations of low thinning. In crown thinning, trees are removed from the middle and upper crown classes in order to open up the canopy and favor the development of the most promising crop trees of these same classes (Fig. 21.6). Formerly, the term "thinning from above" was used for crown thinning, but it is really not appropriate because the method

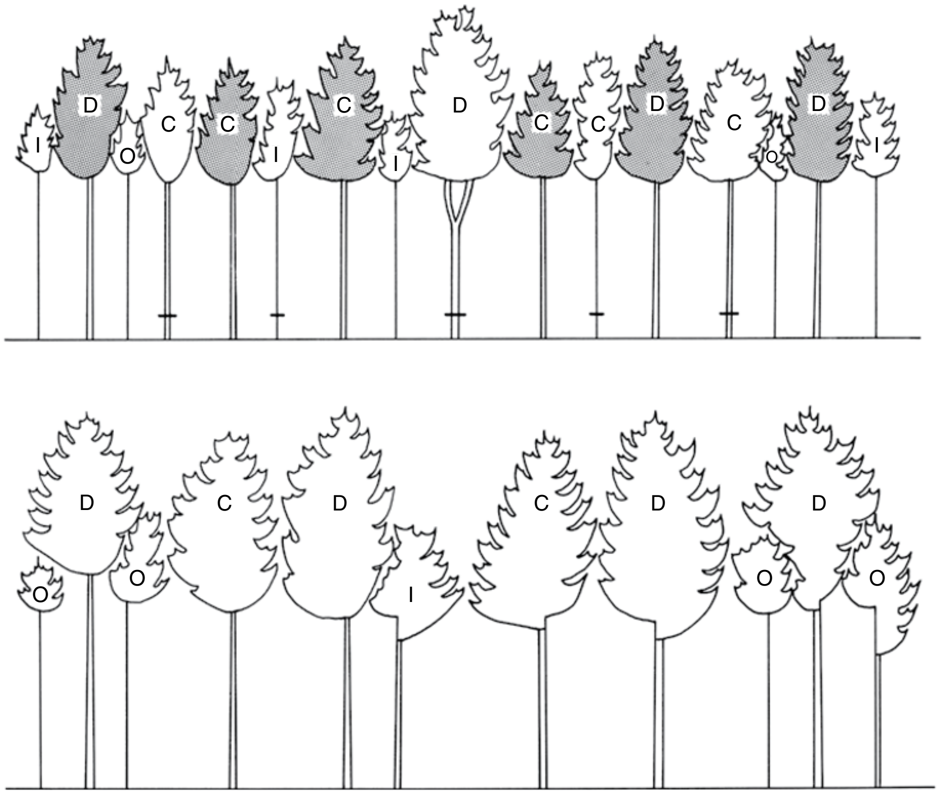


Figure 21.6 A stand of conifers before a crown thinning (top). Selected crop trees are shown with shaded crowns; trees to be cut are denoted by horizontal lines on the stem. The same stand 20 years after the crown thinning (bottom), with the canopy reclosed. *Source:* Yale School of Forestry and Environmental Studies.

does not focus on cutting the tallest trees. The term "thinning from the middle" or "thinning within the upper canopy" is a more logical description. Most of the trees that are cut come from the codominant class, but any intermediate or dominant trees interfering with the development of potential crop trees are also removed. The trees to be favored are chosen from the best-formed dominants and codominants. Crown thinning favors the crop trees to be left by mostly removing a few strong competitors as compared to a low thinning that eliminates a large number of small trees. The question of whether individual dominant or codominant trees are favored is settled according to the relative tree quality. If the codominant has a straighter stem and fewer branches on the lower stem, then the codominant would be chosen; otherwise, the dominant would be chosen.

Crown thinning is a more flexible method than low thinning, but it demands greater skill on the part of the forester. When applying a fairly traditional version of the crown-thinning method, foresters establish an approximate distance for spacing between crop trees. For example, a spacing of 25 ft (7.5 m) in a square grid across a stand would provide 70 trees/acre (175 trees/ha). A crop tree is selected in the vicinity of the first grid location, and one or more competing trees are marked for removal in order to create open growing space for the crop tree. Tree marking continues in this manner for each grid location. If there is no tree that meets the crop-tree quality standards in that location, then the best tree in the vicinity is selected. This method produces a stand with roughly uniform spacing of selected crop trees but with irregular spacing of other trees that are usually smaller and may be clumped, but that are irrelevant to the more uniform growing space made available at the canopy.

Overtopped trees and intermediates that do not interfere with crop trees are not cut in crown thinning. The lower canopy trees serve the useful function of restricting epicormic branching on the crop trees. Their presence also creates a more continuous vertical distribution of foliage, thus creating a more diverse feeding and nesting habitat for animals. Leaving these trees gives a very different landscape appearance than the more open, uniform conditions following a low thinning. One result of crown thinning is the division of the residual stand into two categories of trees. The first consists of the favored dominants and codominants. The second category is made up of the lower canopy trees. Crown thinnings are very compatible with stratified, even-aged, mixed-species stands. Applying a crown thinning to such a mixture evenly opens up the growing space just among the canopy trees.

Usually this means taking out competing individuals of the same species and stratum as the crop trees. The lower-stratum trees are either trees that are slower growing but more shade tolerant that, over time, may become the future canopy, or trees that truly belong in the understory. Crown thinnings accelerate the growth of the crop trees but leave intact the future successional trajectory, species composition, and structure of the stand (Fig. 21.7). It has been used in northern hardwoods to speed up second-growth sugar maple stands to more closely resemble old growth (Singer and Lorimer, 1997). Also, crown thinnings in New England, applied to second-growth oak, have been used to increase acorn mast production for wildlife by over 100% (Healy, 1997).

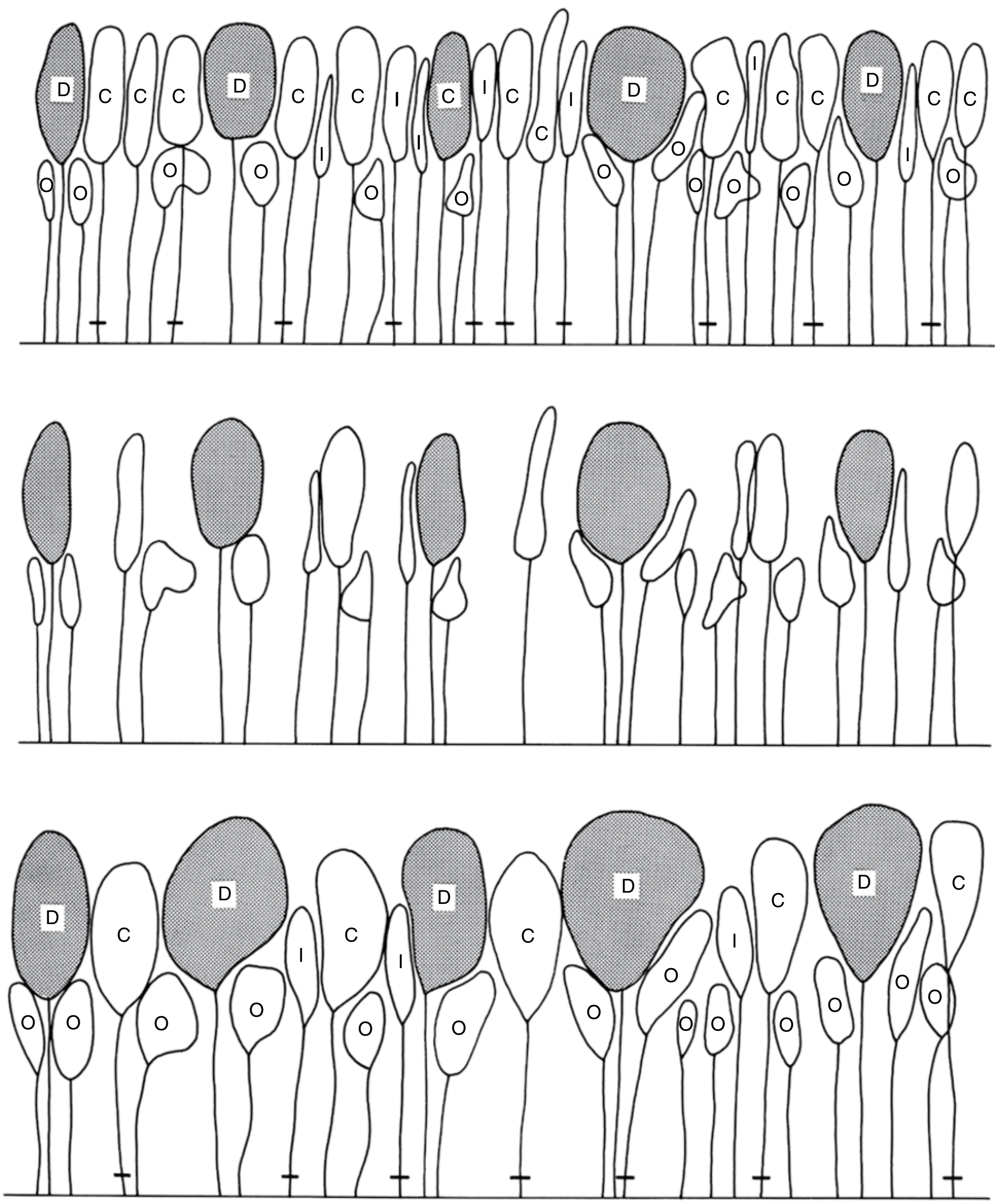


Figure 21.7 A series of crown thinnings in a hardwood stand. The untreated stand is shown before the first crown thinning (top); the trees to be cut are shown with horizontal lines on the lower stems, and the trees chosen as final crop trees are denoted by shaded crowns. The stand is then shown immediately after the first thinning (middle). The stand 20 years later (bottom) is ready for the second crown thinning. Note that a two-storied canopy is being developed by these thinnings. *Source:* Yale School of Forestry and Environmental Studies.

The immediate income return from crown thinnings is greater than that from low thinnings of equal intensity because the trees that are removed are larger. The smaller trees of the lower crown classes, which would be removed in low thinnings, can be left to grow to larger size, or if they are trees of the past canopy that have been overtopped over time, they will eventually die. Foresters sometimes overestimate the growth potential of overtopped trees that are released after a crown thinning. On marginal sites that are droughty or nutrient poor, it is rare that these trees will be able to grow into crop trees, but they can become merchantable trees for mostly low-value products. So a careful knowledge of site and stand dynamics is an important consideration when applying crown thinnings to mixed-species, even-aged stands.

The intensity of the thinning can be determined by the degree of release for each selected crop tree. The crown of each tree can be thought of as a square, and the competition status of the tree is determined by how many sides are touching the crowns of other trees. The thinning decision to be made is whether to release one, two, three, or four sides of the chosen tree by cutting competing trees (Lamson *et al.*, 1990). When a stand is young and crown expansion is rapid, it may be possible and desirable to free the crop-tree crowns on all four sides. In older stands, canopy gaps do not close so quickly and it becomes impossible to release the crop trees completely without substantially reducing the total volume growth of the stand.

An alternative way to determine thinning intensity is to use quantitative techniques such as stand-density diagrams, computer growth models, or other ways to determine a target stand density that would produce the desired stand-level growth after thinning. These two approaches can be combined such that most trees marked for cutting are direct competitors of crop trees, but with the overall intensity of thinning being controlled. This can be accomplished with the use of angle gauges to make quick checks to determine if the marking for crop-tree release is meeting the basal area target (Nowak *et al.*, 1997). This creates a rather complex marking guide, and experienced foresters are needed to apply it, because even with complex models, when it comes to actual marking in a crown thinning, the forester still needs to have an intimate knowledge of stand dynamics (Fig. 21.8).

There are two basic variations of the crown-thinning method that focus strongly on growing large high-quality trees with less concern for stand-level growth. **Crop-tree management** has been developed for mixed-species hardwood stands where there is a very large difference between the value of crop trees and the rest of the stand (Perkey, Wilkins, and Smith, 1994; Miller, 2000; Schuler, 2006; Miller, Stringer, and Mercker, 2007). This thinning method was developed in the central Appalachian Mountain region, but could be applied in many other areas. Many young hardwood stands develop with high stem densities, and they are left in that condition to produce good stem form. Thinning can begin at the age when the desired height of clear stem has developed, usually a 16-ft (4.8-m) log. The maximum number of crop trees to release is about 60 trees/acre (150 trees/ha), but there may be many fewer than that in parts of the stand. The ideal thinning approach is to completely release all four sides of each crop tree, and this method is repeated after the competing trees grow and come in contact with the crowns of the crop trees. Where there are no trees that meet the quality standards for crop trees, no cutting is done. This pattern of thinning creates a more irregular canopy density across the stand, compared to the standard crown-thinning method. This is a much simpler method to follow, compared to those that include a stand-level, basal-area density control. At the end of the rotation, the crop trees are harvested, so there will be an irregular pattern of openings where crop trees had been cut and dense patches of smaller poor-quality trees had not been thinned.

A type of thinning that is related to crop-tree management is called **low-density thinning** (or low-density management). It has been used mainly in conifer plantations and single-species stands, and in natural conifer stands. The goal is to produce large, high-quality sawlogs very rapidly. An early trial of this method was with loblolly pine plantations in Arkansas, and the term "sudden sawlog" became associated with the method (Burton, 1982). In this trial, the plantation began with 1200 trees/acre (3000 trees/ha) and was thinned to 100 trees/acre (250 trees/ha) at age 12. In the next 21 years, there were three thinnings, reducing the density to 50 trees/acre (125/ha); pruning produced clear stems 32 ft (9.6 m) in height. At age 33 years, the stand contained 50 trees/acre (125 trees/ha) with a mean DBH of 18 in (45 cm). This might be considered a series of very heavy crown thinnings where all crop trees are identified early and subsequent crown thinnings are made, removing all direct competitors in the canopy first, but in the end it looks like an open-grown, evenly spaced, uniformly sized, single-species stand with no structure in the understory. If one did not know how the approach to the thinning proceeded over time, it could have been identified as a very heavy low thinning (Fig. 21.8). If the stand reaches reproductive maturity, the last thinning could easily be taken as the establishment cut of a shelterwood or seed-tree regeneration method if the intent was to regenerate the stand at the same time as the canopy trees.

Eastern white pine has been managed similarly in New England (Seymour and Smith, 1987; Seymour, 2007). In this case, stands were grown in dense plantations or natural stands, and then thinned to 60–100 trees/acre (150–250 trees/ha) in a single treatment at age

(a)

(b)

Figure 21.8 (a) A stand before a crown thinning in a 55-year-old eastern white pine stand (orange circles denote crop trees). Trees with blue dots at the base are competing trees that will be cut. *Source:* Mark S. Ashton. **(b)** A crown thinning in a second-growth even-aged mixed-hardwood stand that has focused entirely on spacing the canopy dominant and codominant oak trees (as demonstrated by orange circles). All other sub-canopy trees (hemlock, red maples, sugar maple and black birch) have been left alone. *Source:* **(a, b)** Mark S. Ashton.

20–30 years. Pruning of dead branches was done to a 16 ft (4.8 m) height. Much growing space is wasted because of understocking at this early stage after thinning, but small knotty white pine has little value. In general, tree species with narrow crowns could produce 100 trees/acre (250 trees/ha) as the maximum density for growing in open conditions. For species with broader crowns, 60 trees/acre (150 trees/ha) would be the maximum (Page and Smith, 1994; Seymour, 2007; Guiterman, Weiskittel, and Seymour, 2011). This is similar to the

number of crop trees for broad-crowned hardwood species described earlier, but a drastic thinning to leave only the 60 crop trees/acre (150 trees/ha) would likely cause development of epicormic branches in many species, so this method is not appropriate for many hardwood species. Elsewhere, the most obvious example in the tropics is the low-density, crown-tree release work by Baker, Robinson, and Ewel (2008), with single-species, single-aged stands of *Acacia koa* in Hawaii.

Dominant Thinning

The method of dominant thinning is considerably different in principle from the two methods already discussed. It is also appropriately referred to as **thinning from above**. The term **selection thinning** has also been used for this method, because of its resemblance to the selection method of regeneration in uneven-aged stands. The term "dominant thinning" will be used to avoid confusion with the selection method. In dominant thinning, dominant trees are removed in order to promote the growth of trees of lower crown classes (Fig. 21.9). The same kind of vigorous trees that are favored in crown thinning and heavy low thinning are the very ones that are likely to be cut in dominant thinning. It is obvious then that this method is suitable only for specific purposes. If it is used carelessly, it can easily become a form of high-grading (harvesting the best largest trees and leaving the poorest). There are several situations in which stand conditions and management goals may benefit from the use of dominant thinning, which are described below.

One-Time Applications of Canopy Dominant Thinnings

Removal of Poor-Quality Dominants

The first situation for dominant thinning comes about when a young stand begins to differentiate into crown classes. With some stands, irregular spacing allows trees that are in open areas to grow large and branchy crowns. The same may occur with trees that were slightly older than the rest of the stand. In other cases, poorly formed dominants can result from damage by insects and disease, or wind, snow, and ice. Also, in mixed-species stands, an undesirable pioneer species may grow rapidly into a dominant position, above more shade-tolerant species. Many pioneer species have short lifespans, so treatment would not be needed, but some of these species can persist for very long periods (e.g., red maple, black birch, yellow-poplar).

The dominant thinning method removes dominant trees of poor quality in order to favor the satisfactory

(a)

(b)

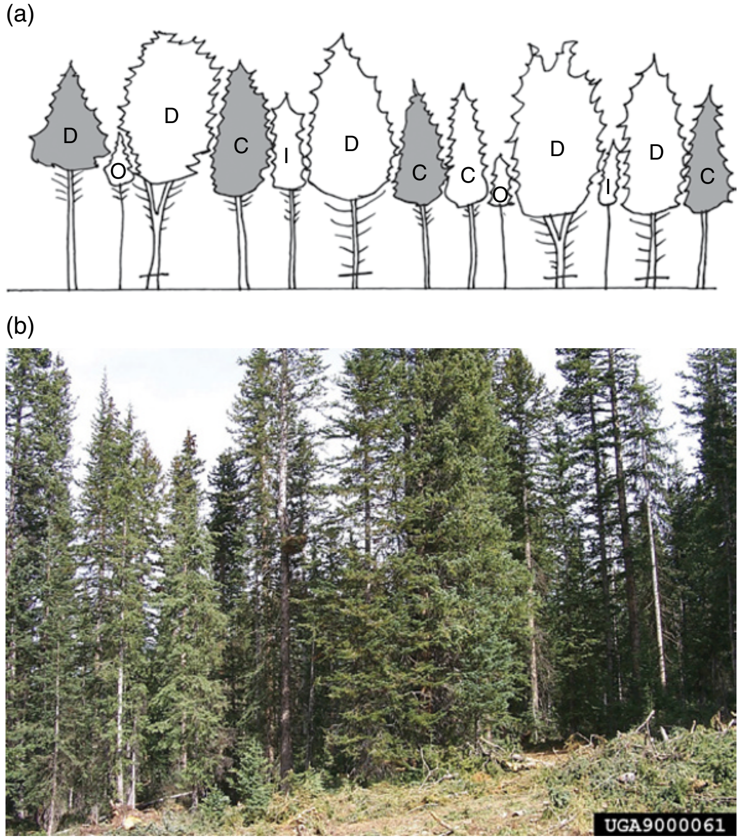


Figure 21.9 (a) A stand of conifers marked for a dominant thinning (selection) aimed primarily at the elimination of poorly formed dominants (with horizontal lines on their stems) and the release of less vigorous trees of better form (with shaded crowns). The next thinning would not come until the large holes in the canopy had nearly closed and it would logically be a crown or low thinning, not another dominant thinning. *Source:* Yale School of Forestry and Environmental Studies. (b) An Engelmann spruce–subalpine fir stand that has had a dominant (selection) thinning in the Uinta National Forest. *Source:* US Forest Service.

crop trees. The removal of these trees creates growing space for codominant and intermediate trees as well as some of the dominants that have straighter boles and fewer low branches than the most vigorous dominants. Dominant thinnings designed to improve the quality of the crop trees are best carried out as early as possible in the life of the stand and then replaced by other thinning methods.

An example of this kind of application of dominant thinning is found in stands that contain tree species that are attacked by the white pine weevil (*Pissodes strobi*); these include eastern and western white pine, Sitka spruce, and red spruce. The female weevils choose the large leaders of the dominant trees to lay their eggs. After the larvae emerge, they feed on the cambium of the leader, which kills the shoot. The death of the leader causes a loss of apical control in the upper branches of the tree, so those branches begin to grow vertically, producing a poor-quality, multi-stemmed tree. Thus, stands of these tree species often have poorly formed dominants while the codominant and intermediate trees have very good form because they were not affected by the weevils. If there is no market for these, trees girdling or stem injection with herbicide is the only alternative to kill these poorly formed dominant pines.

Species Conversion of the Canopy Stratum

Another example of applying a dominant thinning includes the intentional species conversion of the largest trees in the canopy of even-aged, second-growth, mixed-species forests. By doing this, a canopy comprised mostly of shade-intolerant species changes to a canopy of shade-tolerant species. A good example in northern hardwoods is when birch is removed in order to accelerate the growth of maple and beech (Leak, 2007). In northeastern forests, second-growth hardwood stands on fertile sites involve removing dominant oaks to release sugar maple. For example, done in the right circumstance, this can accelerate successional processes and convert a stand valued for timber (e.g., oak) to one valued for its sap (e.g., sugar maple). But if it is done with the wrong species combination and site, this can easily lead to the kind of high-grading mentioned earlier (Fajvan, Knipling, and Tift, 2002; Dwyer *et al.*, 2004). In fact, some stands that have been repeatedly high-graded from diameter-limit harvests (both in the tropics and in temperate moist forests) have ended up as almost pure vegetative stands of understory trees (e.g., *Carpinus* spp.).

Removals to Allocate Growing Space to the Understory

The third example of one-time removals of the canopy using dominant thinning can involve taking out the largest trees of either even-aged or uneven-aged mixed-species stands to allow more light to the sub-canopy and understory plants for the cultivation of various kinds of NTFPs that do well with a little more direct sunlight. Examples are some of the sub-canopy fruit trees in tree gardens in the moist tropics of Central America and southeast Asia: *Annona* spp. (soursop, sugar apple, custard apple); *Nephelium* spp. (rambutan); *Garcinia* spp. (mangosteen) (Fig. 21.10). These species do not necessarily do well together in the understory because of their susceptibility to the density-dependent effects of insects and pathogens. Thus, the creation of a more heterogeneous canopy structure allows light to penetrate to the understory in ranges of opening sizes. Low thinnings have a light regime that is uniformly raised across the complete understory, making conditions more suitable for NTFP cultivation of plants that are not susceptible to density-dependent pathogens and diseases, and that can be cultivated more uniformly across the stand.

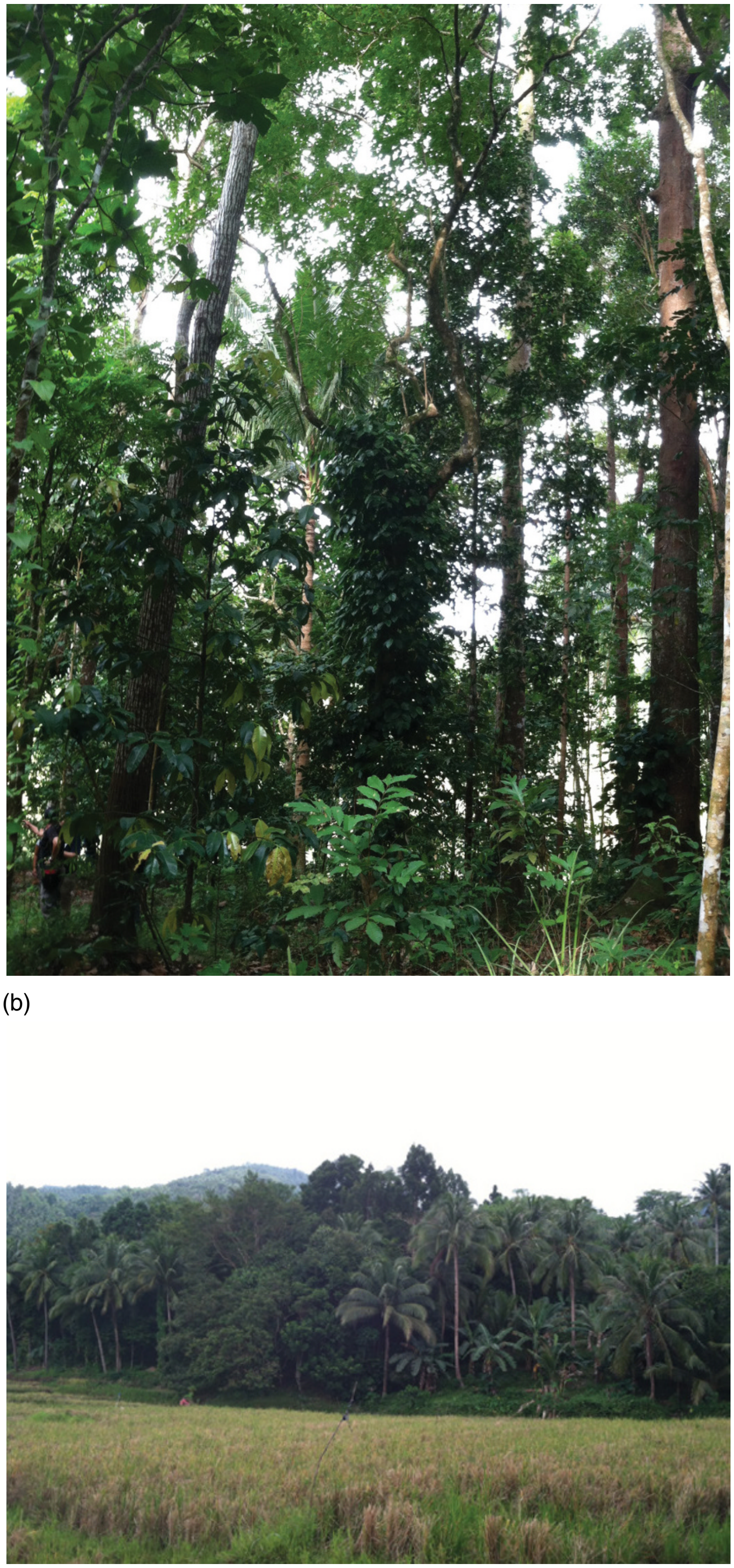
Repeated Removal of Dominant Trees

Diameter-Limited Systems

The second situation in which dominant thinning is appropriate, occurs when the management objective is not to develop large sawlog trees, but to grow a large number of trees to medium size for pulpwood, small sawlogs, posts, poles, or pilings. In this type of management, a minimum target diameter is chosen, and all trees larger than that diameter are cut. In mixed-species stands, different target diameters may be used for different species. This kind of cutting can then be repeated, but lower canopy trees do not always respond in growth as much as managers wish. The target diameter often needs to be reduced as fewer trees reach the original target diameter within the timing of the cutting cycle (Angers, Messier, and Leduc, 2005; Gronewold, D'Amato, and Palik, 2010). If these kinds of thinnings are repeated, they will amount to diameter-limit cuttings, leaving the stand with old, poor-quality trees and large canopy gaps. At some point, the series of thinnings needs to be stopped, and silvicultural planning should shift to regeneration treatments for the stand.

The stands with the greatest capacity to endure repeated dominant thinning are of species that are both shade tolerant and have strong apical control, which allows them to maintain a single leader, even when growing in low light (Fig. 21.11). Many conifers have these characteristics. The lower crown classes of these species are likely to show a response after larger trees have been cut, with rapid growth, straight stems, and high live-crown ratios. Stands of intolerant species cannot withstand more than one or two dominant thinnings before most of the trees capable of growth response are gone (Clay Smith, 1980; Fajvan, Knipling, and Tift, 2002). Many hardwoods have poor apical control and become deformed if they have grown underneath larger trees.

(a)



(b)

Figure 21.10 (a) A dominant (selection) thinning in an all-aged mixed-species tree garden in Leyte, Philippines. (b) A view of the tree garden across the paddy field. *Source:* (a, b) Mark S. Ashton.

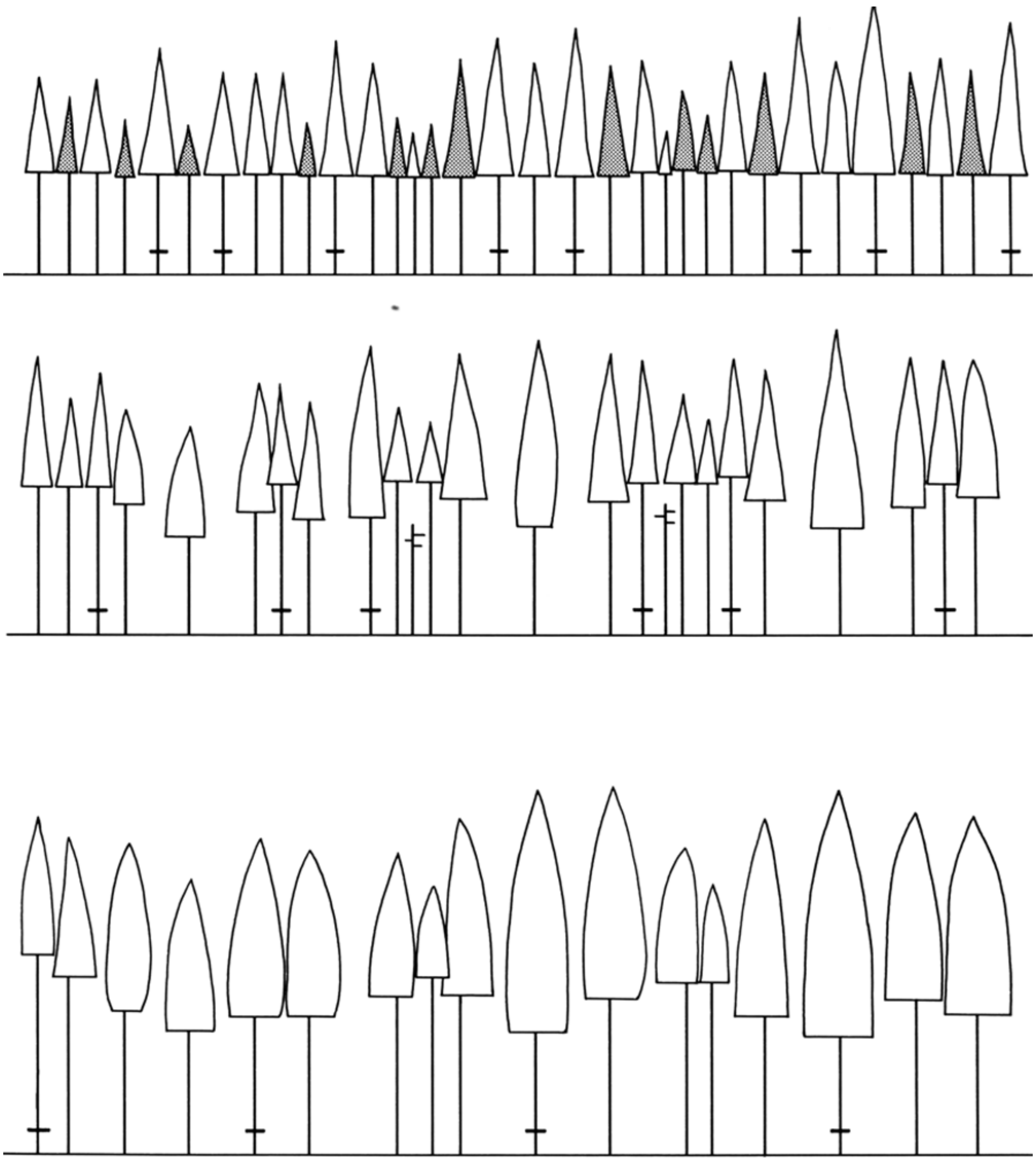


Figure 21.11 A series of three dominant thinnings in a stand of balsam fir and red spruce. Each sketch shows the stand immediately before a thinning, with the trees marked to be cut. The trees with the shaded crowns in the top sketch are those that survive until the end of the rotation. The choice of trees to be removed in the second and third thinnings is somewhat modified in order to avoid enlargement of the gaps caused by the earlier removals of dominants. *Source:* Yale School of Forestry and Environmental Studies.

If they do respond to increase in growing space after dominant thinning, they often develop multiple leaders, which causes forking in the stem.

One reason that dominant thinnings are used is that they are more likely to return an immediate profit than any other kind of thinning (Erickson, Reed, and Mroz, 1990). The trees that are cut are ordinarily the most merchantable to be found in the stand. Excessive attention to this short-term financial return often leads to high-grading. The total value removed from the stand over the rotation may be greater, but the rotation will be longer as growth is consistently shifted to trees with lower vigor.

Almost all methods of repeated dominant thinnings produce trees that are likely to have low vigor and weak and slender stems. Insects and diseases are more likely to attack these trees. Dominant thinning tends to aggravate problems with wind damage because it removes the

strongest trees that are the most windfirm. If the weaker trees do not have strong trees protecting them from the force of high wind and snow, they are apt to blow over and create more of the small gaps in the crown canopy, which can cause even more blowdown.

Repeated dominant thinning produces slower-growing trees that are undesirable from the genetic standpoint, but the choice against poorly formed trees of any size would be desirable (Li, Bousquet, and MacKay, 1992; Buchert *et al.*, 1997). It is unclear whether the degree of selectivity and of heritability are great enough to cause major change in the average characteristics of any new natural regeneration, but the rare, best genetic combinations are likely to be eliminated.

This mentality of repeated dominant thinning is rampant in the tropical rainforests, where almost all are managed on cutting cycles that have progressively become longer and longer (e.g., starting at 15 years and moving to 40 years) as prior assumptions of growth and productivity have proved erroneous (Bertault and Sist, 1997; Jackson, Fredericksen, and Malcolm, 2002; Sist *et al.*, 2003a, 2003b). Diameter-limit cuts in these circumstances have also declined with each cycle, starting with the first cutting of the primary forest at 24 in (60 cm) and moving to 12 in (30 cm) after two or three entries (see Chapters 13 and 25 on selection systems and forest-restoration processes respectively).

Free-Form Thinning

In many situations, a mixture of two or more methods may be needed for a single thinning operation. The greatest need for combining methods is encountered in stands that are somewhat irregular in age, density, or composition. Free-form thinning includes any one of a combination of low, crown, and dominant thinning. This approach to thinning is spatially explicit, where in some parts of the stand there is low thinning and in other parts crown thinning and still other parts dominant thinning. Such an approach is useful for stands that are usually of second-growth origin with species mixtures that have established in a variable and clumped arrangement, and/or where past land-use histories of human (logging) and natural (ice storm) disturbances have created irregularities in species composition and stand structure. Implementing a free-form thinning is an appropriate remedy to create a more uniform stand structure and species composition.

Sometimes, the term free-form thinning is used whenever a particular thinning does not conform exactly to the definitions of any of the methods. This should be avoided, because the only information that the term gives is that it is some kind of thinning. A better approach is to use concise descriptions of the combinations or modifications, as in the following two examples: (1) in a young unthinned, uniform stand, a thinning operation might simultaneously include dominant thinning to eliminate scattered dominant trees of undesirable pioneer species, and crown thinning to release codominant crop trees; (2) in an irregular stand made up of a matrix of conifers with patches of valuable hardwoods, a thinning might include low thinning of the conifers, and crown thinning in the hardwood patches. These two brief descriptions give much more information than using the term "free-form thinning" for all combined or modified thinning operations.

Free-form thinning is probably the most common kind of thinning treatment on private forest woodlots in eastern North America (Miller, 1997). Many of these forests have had land-use histories of timber exploitation, fire, and untreated insect and disease outbreaks that make the stand heterogeneous in structure and composition. Their variable structure and pattern of species distribution make them ideal targets for free-form thinning if the goal after thinning is to create a more uniform structure and species composition for future timber production.

Variable-Density Thinning

The most recent addition to the set of thinning methods is variable-density thinning (Carey, 2003; Harrington, Roberts, and Brodie, 2005; O'Hara *et al.*, 2010). It has been devised to create a more complex forest structure than is generally found in managed even-aged stands. Uniform tree spacing is a basic principle in most thinning methods for timber management. As described earlier in the chapter, foresters use species, tree vigor, and stem size and quality, for selecting trees to be retained in a thinning, but these characteristics are also combined with uniform spacing of crop trees to grow the largest number possible of these crop trees. In contrast, the variable-density method purposely creates irregular tree spacing. The goal is to promote a greater variety of ecological conditions than would normally be found in a uniformly spaced stand, and in general to foster an increase in biodiversity in the stand. Thus, variable-density thinning can be conceived to be almost equal and opposite to free-form thinning. Free-form thinning seeks to use a combination of low, crown, and dominant thinnings to treat a heterogeneous and uneven canopy structure, with mixed but clumpy species composition to make the stand more uniform in structure and species composition. In contrast, variable-density thinning seeks to change a stand that is uniform in structure and species composition, to a stand that is more uneven in canopy and more clumpy and irregular in species composition.

Variable density thinning has been used mostly with Douglas-fir plantations in the Pacific Northwest and

British Columbia. Most plantation management includes fairly uniform spacing, both at the time of planting and after each thinning. The amount of understory vegetation in a plantation generally varies with both the leaf-area density of the crop species and the stand density as affected by thinning practices. Some stands of shade-tolerant species have canopies so dense that few organisms exist on the forest floor and litter tends to accumulate. The basic characteristic of variable-density thinning is the establishment of both canopy gaps and dense unthinned patches in uniform stands. It is most logical to link these treatments with another thinning method. This would mean applying low thinning, crown thinning, and dominant thinnings in different parts of the uniform-canopied stand with an even stem-density distribution, and perhaps leaving other parts unthinned.

As an example, a thinning prescription might consist of a low thinning in 75% of the stand, with 15% of the stand in gaps of 0.1 acre (0.04 ha), and with 10% of the stand in unthinned patches of 0.5 acre (0.2 ha) (Fig. 21.12). The cutting is not complicated once the gaps and unthinned patches are marked. The low thinning is carried out as normal: when an unthinned patch is encountered, there is no cutting or moving equipment through the patch, but when a gap is encountered, all main canopy trees are cut except for species that are not the main species of the stand. The unthinned patches are designed to create dense-shaded heterogeneous habitat, with an accumulation of snags, coarse woody debris, and thick forest-floor litter. Gaps create open habitat with vegetation of shade-intolerant species, greater litter decomposition, and sparse trees of less common species in the stand. If substantial shade-intolerant vegetation is desired, the gap size would likely need to be enlarged beyond 0.1 acre (0.04 ha), but it is not intended to create a different kind of habitat. The gap is not intended for regeneration or as a regeneration method (Harrington, Roberts and Brodie, 2005).

Figure 21.12 An Engelmann spruce variable-density thinning on the San Isabel National Forest, Colorado, that originated as a planting with some natural regeneration that established later. *Source:* D. Powell, US Forest Service, Bugwood.org. Reproduced with permission from Bugwood.org.

The variable-density method would be appropriate for treating natural stands as well. They may already have greater variability in spacing and species composition than plantations, but thinning tends to move them toward more uniform canopies. Although the response to gap creation in variable-density thinning can be partly predicted from the abundant canopy-gap research that has been conducted for regeneration objectives, the impacts of the use of various gap sizes and spacing in young dense stands (especially plantations) are not yet known.

Geometric Thinning

In geometric thinning, the trees to be cut or retained are chosen on the basis of a geometric spacing pattern, rather than on their species, stem quality, or canopy position. This method is sometimes called **mechanical thinning**, given the fact that the stands are thinned by machines with almost automated precision and with little individual tree choice. Geometric thinning is generally used only for the first entry into a stand. Many times these first-time thinnings are **precommercial** and sometimes they are confused as release treatments. By definition they are thinnings, because the stands being treated are beyond the sapling and pole stage of development. Compared with the other kinds of thinnings, they are the least efficient in leaving a uniform amount of growing space to the remaining trees because of the very fact that the choice of tree removed is so fixed and regimented. It is a sacrifice that is made, given the necessity of thinning for lower cost and time. There are two stand conditions where geometric thinning is generally used. One condition consists of natural stands that are very closely spaced and have not yet developed much crown-class differentiation. The other consists of young plantations that are ready for a first thinning. In both cases, these early thinnings are meant to set the stage for using other thinning methods that have more opportunity for tree-by-tree selection for cutting or retaining.

Natural Dense Stands

Extremely dense stands can occur in many forest types. They often develop naturally from a combination of large seed crops and favorable climatic conditions, which produces dense establishment. Human activities can also create very dense stands in similar ways, particularly when the use of direct seeding works better than planned, and crowded regeneration stands develop. These situations tend to be most relevant to single-species stands, where trees begin competing very early in stand

development; individual tree growth is slow, and so crown-class differentiation develops slowly as well, with competing trees all having a similar autecology and structure. In some cases, stands are so dense that height growth is reduced compared to more open stands on the same site conditions. The colloquial term that has been used for this kind of stand structure is a "dog-hair" stand. The most common species that reach these extremes in density are hard pines including lodgepole, ponderosa, jack, loblolly, and red pines (Tong, Zhang, and Thompson, 2005; Stark *et al*., 2013).

Two types of geometric thinning are used in these crowded stands. **Strip thinning** consists of cutting or crushing trees in parallel strips through a stand. Rolling brush-cutters and bulldozers or tractors with rotary blades or saws are generally used for these purposes. The material can be left as slash in the cut strips, or it can be chipped if fire danger is high (wood chips form a compacted layer on the forest floor which reduces flammability). The objective is to release growing space for trees on the edges of the leave strips. The crowns of some of these trees will expand into the cut strips. Ideally, the larger crowns will allow some of these trees to increase height and crown growth rates and suppress adjacent trees. Acceleration of stand differentiation is the important goal. This kind of treatment is rather crude, but is often the only approach that is feasible and it is done as an investment for future stand production. There will generally be little or no income from the operation, so costs must be kept low. The next thinning would likely be a crown or low thinning, and it would be a commercial harvest.

An alternative treatment for the stands described above is **spacing thinning**. In this method, trees are selected and flagged at fixed distances, for example, in a square grid of 25 ft (7.5 m) on a side. All other trees in the stand are cut, usually with chainsaws or brushsaws. This method is often modified to allow some selection of trees based on species, size, and tree quality. In those cases, the trees to be retained are chosen as the best tree within a certain distance from the fixed grid location. As with strip thinning, this operation would be a precommercial thinning.

Young Plantations

The traditional design of plantations has been to plant seedlings in straight rows with square spacing, and this is still frequently used. The initial spacing of the seedlings in these rows takes into account the need for early crown competition between trees in order to shade and kill lower branches, thus creating good stem form. After this process has progressed adequately, the next step is to reduce stand density to stimulate faster tree growth. However, it can be quite difficult to fell trees in a dense young plantation. One solution for dealing with this problem is to use **row thinning**, which consists of removing entire rows through the plantation (Figs. 21.13, 21.14). Harvesting equipment can enter the stand to fell and extract all trees along the row. The removal of alternate rows (one-half of the stand) would generally be too severe. A standard method is to cut every third row; the removal of one-third of the stand is a close approximation of the normal severity of thinning in young stands. This one-third removal method provides growing space for every residual tree, but only on one side. These cuts produce trees with asymmetric crowns just as in the dense natural stands that are cut in strips, as described in the previous paragraphs. The principle is the same: each tree crown will expand in one direction (into the cut row), but later thinnings will free more growing space to allow crowns of the best trees to expand in all directions. In the southeastern US, young loblolly pine plantations are often thinned with a combination of cutting every fifth row to open the stand and then selectively removing trees within the remaining 80% in order to reach a stand level of 70–80 ft^2/acre (305–350 m^2/ha).

Plantation managers have further developed initial spacing patterns that improve the efficiency of the first thinning. This allows the young stand to reach the appropriate stage for thinning at a time when the trees to be cut are large enough to be used for pulpwood or similar products based on small trees. One method is to plant seedlings on rectangular spacing, such as 10×6 ft (3×1.6 m), rather than square spacing. This allows heavy equipment to enter the stand along one of the wider rows, cutting all the trees in that row and thus creating a lane that is 20 ft (6 m) wide for maneuvering. In this method, every fifth row is cut, and then the principles of low thinning or crown thinning are used to remove selected trees in the two rows on each side of the cut row (Fig. 21.15). If skidders are being used, it helps to fell these trees in a herringbone pattern with the butts pointing in the direction of the landing. In this case, the extraction pattern may control the trees that can be cut. However, this problem does not exist when harvesting machines with saws on long mechanical booms are used. These can reach into the two rows on either side and cut any tree, and then carry it upright and lay it in the cut row for extraction. The combination of 20% of the trees removed by cutting all in every fifth row, plus 25% removal for thinning the other four rows, results in a removal of 40% of trees. This is a common thinning intensity, but can be varied with the percent of trees removed from the leave rows (Mäkinen and Hongisto, 2006). The kinds of plantations where this type of thinning is widely applied as a first-time thinning are the single-species plantations that are grown primarily for dimensional timbers (e.g., loblolly pine, slash pine, radiata pine, *Eucalyptus* spp., Douglas-fir, Scots pine, Norway spruce, *Acacia mangium*, and teak).

(a)

(b)

Figure 21.13 **(a)** A row thinning being started in a dense 25-year-old plantation of red pine in New York. Every third row is being removed. **(b)** A 15-year-old loblolly pine plantation on the coastal plains of South Carolina with a geometric thinning removing every third row.
Source: **(a, b)** Yale School of Forestry and Environmental Studies.

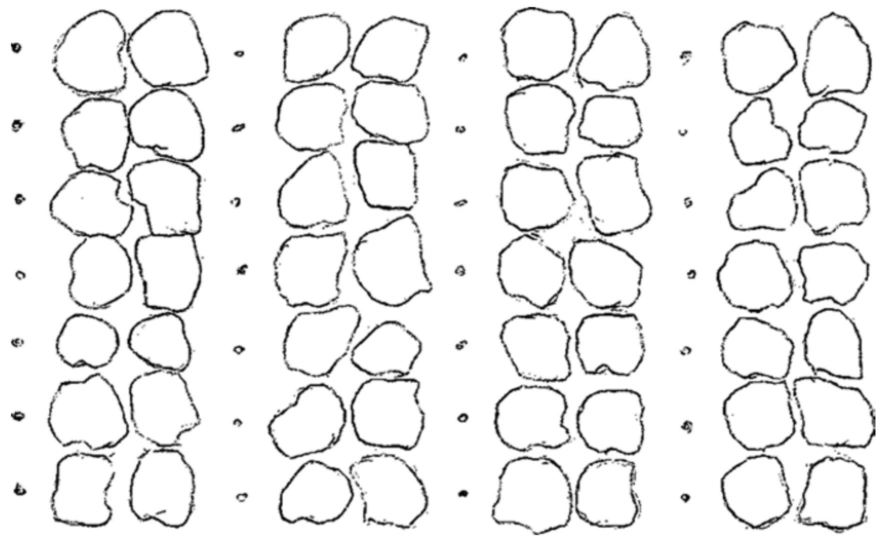


Figure 21.14 The pattern of live tree crowns and cut stumps left after a row thinning that has removed every third row, as seen from above. Each crown has been released on one side. *Source:* Yale School of Forestry and Environmental Studies.

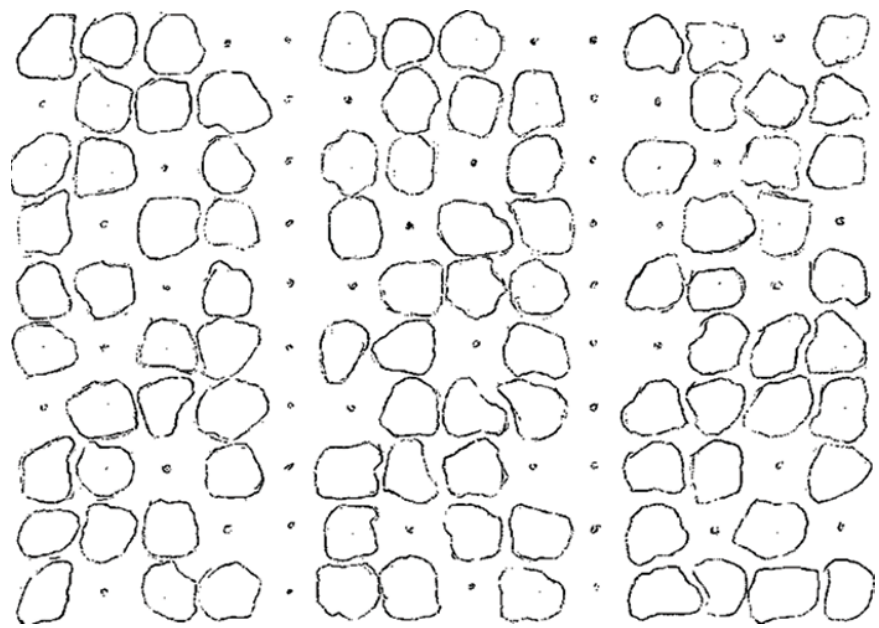


Figure 21.15 The pattern of live tree crowns and cut stumps left after a row thinning that has removed trees in every fifth row, and then removed 25% of the trees within the rest of the rows by reaching into the two rows on each side of the cut row. Trees have been released on one, two, or three sides. *Source:* Yale School of Forestry and Environmental Studies.

Application of Thinnings

A schedule of thinning should be a systematic plan that includes the kind of vegetation, wood products, ecosystem, and social benefits that are desired. The ultimate objective is to move the stand toward a desired future stand condition, which would usually be at the end of the rotation, or when a particular stand structure has been established. The plans for thinning treatments should focus on those objectives, but they should remain flexible enough to make changes based on the stand conditions at the time of each treatment.

The planning of a thinning program for a stand includes:

1) the choice of thinning methods, which may change over time;
2) the timing of the first and subsequent thinnings;
3) the stand density as influenced by the intensity of thinning.

Thinning Methods

One way to compare the impacts of the various thinning methods on a stand is to plot the general pattern of each diameter distribution (Fig. 21.16). Three of the thinning methods involve harvesting trees from different segments of the diameter distribution. It is rare that a single method can be used through an entire rotation. It may seem

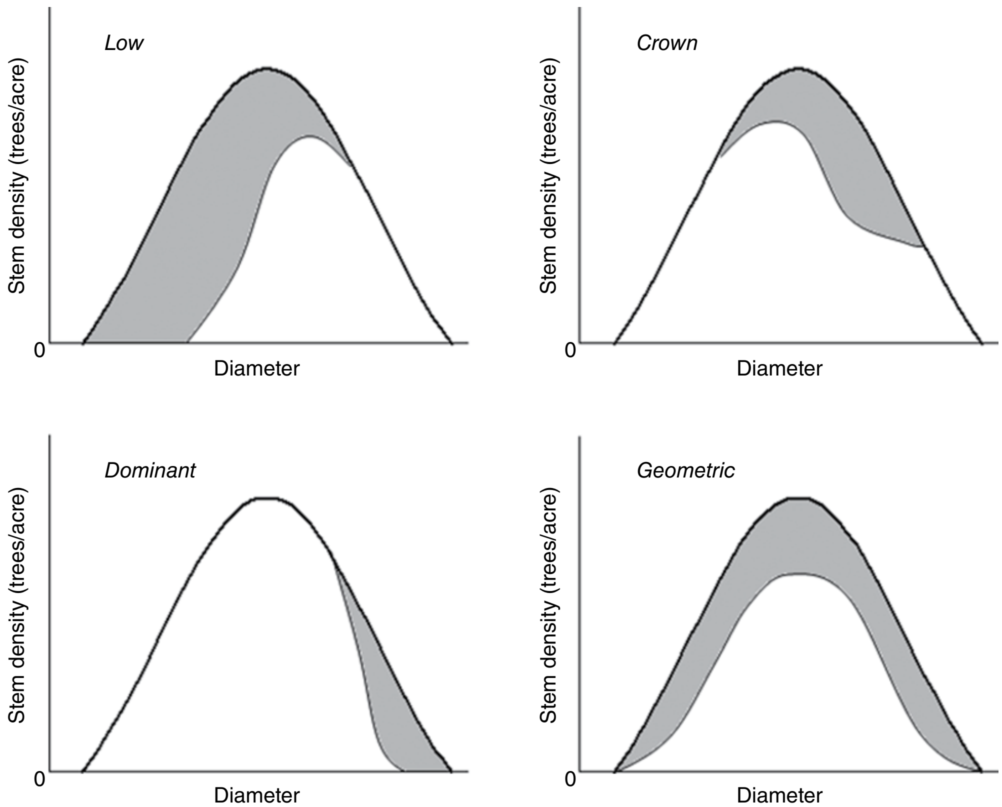


Figure 21.16 Diameter distributions for the same pure, even-aged stand, showing by cross-hatching, the parts that would be removed in four different methods of thinning. In each case about one-third of the basal area is represented as having been removed. *Source:* Yale School of Forestry and Environmental Studies.

logical to use low thinning initially to follow the natural pattern of stand development. However, this would generally mean cutting small non-commercial trees. One approach to avoid cutting small trees is to first use dominant thinning to remove the large, poor-quality dominant trees (if these exist in the stand), then later shift to crown thinning, and then to low thinning, when the small trees have increased in size with age and overstory thinning. These will still not be large crop trees, but they will at least be merchantable for low-value products. In other situations, where geometric thinning of plantations or dense young natural stands has been used, the intention is always to use this only as a first thinning, but then to shift to another method that uses tree-by-tree selections for retaining or cutting during thinning. However, there are too many different objectives and stand conditions to be able to outline a standard series of thinning methods for all situations. The different approaches are summarized in Table 21.1.

Timing of Thinnings

The decision about when to conduct the first thinning is a combination of the biological development of the stand and the economic possibilities of income from the trees to be removed. The first thinning can be made as soon as the crown competition has progressed enough for the trees to start to interfere with one another. The best single criterion for determining when to apply the first thinning is the **live-crown ratio** (**LCR**) of the potential crop trees. A planned reduction in LCR is usually desirable to promote natural branch pruning and restrict the degree of stem taper, but a loss of diameter growth will result if LCR is reduced too much. In many species, an LCR of 30–40% is appropriate for the balance between these two factors. The stand age at which that point is reached depends on the initial spacing and tree growth rates.

Economic factors often control the timing decision, delaying the first thinning until the trees planned for removal become merchantable. If funds are available for long-term silvicultural investments, the first thinning can be done as an investment that will provide benefits in the faster growth of a stand. If such investments cannot be made, the first thinning must be delayed until the stand will give an immediate profit. However, economic analyses have repeatedly shown that precommercial thinning often is the most rewarding long-term silvicultural investment.

The effects of a single thinning are not maintained indefinitely. After a few years, the gaps in the canopy

Table 21.1 A comparison of the different approaches to thinning, their advantages and disadvantages, and the kinds of stand conditions that are most applicable to their use.

Thinning approach	Appropriate applications	Inappropriate applications
Low thinning	Single-species, natural and plantation stands, ideal for lifting the canopy to cultivate understory crops creating pastures and views, and reducing fuel-loads	Mixed-species stands where species grow at different rates or are uneven-aged (all-aged); difficult to implement if no market for small-diameter trees
Crown thinning	Mixed-species, even-aged stands where species grow at different rates and where canopy trees are of the same functional guild	Not appropriate to apply to uneven-aged (all-aged) stands
Dominant thinning (selection)	Converting even-aged stands with a shade-intolerant canopy to a shade-tolerant species growing beneath. Promoting smaller shade-tolerant trees in uneven-aged stands	In an even-aged, mixed-species stand, removing the large trees that are shade intolerant with the assumption that they will be replaced by the same species
Geometric thinning (mechanical)	Single-species plantations where commercial markets can use variably sized trees	Large trees of high commercial value
Free-form thinning	A heterogeneous stand and species structure perhaps from past land-use history that now needs to be more uniform	Creating a variable wildlife habitat
Variable-density thinning	A homogeneous stand and species structure usually originating as an even-aged stand that now needs to be converted to one with variable structure	Growing trees/crops for maximum yield

Source: Mark S. Ashton.

close together, and before long, the same crowded condition redevelops. As the crowns expand, the growth rates of trees decline, and surplus trees become available for commercial harvest in the next thinning, and individual tree growth rates will increase as a result. The heavier the thinnings, the longer is the interval between them. Heavy, infrequent thinnings tend to reduce the total yield of a stand because of the long periods during which the growing space remains unoccupied. Light thinning leaves the canopy more closed and thus reduces the loss in total wood yield. The rate of growth of the crop trees is a good criterion for determining when thinnings should be repeated.

Tree size, crown class, and general ideas of spacing have been presented in this chapter for describing the principles of thinning. However, there are many quantitative techniques that deal with growth and yield to guide the management of stands. These are the focus of Chapter 22.

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22

Quantitative Thinning: Theory and Application

Introduction

A program of thinnings is essentially a series of temporary reductions made in stand density (measured in terms of basal area or some similar parameter). Thinnings are made for many non-market objectives such as improving water quality and watershed protection, aesthetics and viewsheds, and wildlife habitat (see Chapter 21). However, when precise knowledge must be known about how much and when to thin, such information is mainly driven by decisions to maximize the net value of wood products removed during the whole rotation. This chapter concerns the quantitative underpinnings of thinning guidelines that are mainly focused on increasing merchantable yields from dimensional wood products. The chapter can be divided into two parts. The first part covers the conceptual and experimental proof behind the application of thinning to improve merchantable yields. The second part covers the quantitative guidelines with sections on each approach, and when and where it is applicable.

Conceptual and Experimental Proof for Thinning

Thinning and its Objectives

Quantifying Objectives

The quantity, quality, utility, and size of wood products, as well as the costs of harvesting and manufacture, are the main factors determining the net value. Production in terms of quantity or volume of wood is usually considered to be the factor of greatest importance. In this connection, clear distinctions should be drawn between all of the different ways in which the growth and yield of stands and trees are measured. Thinning practice cannot be adequately understood without a thorough comprehension of the relationships between the very different mensurational units in which growth and its value can be evaluated. Unfortunately, conventional mensurational parameters are, at best, only preliminary approximations of this value, mainly because they do not automatically reflect the variations in value associated with tree diameter and wood quality. It should not be inferred in any situation that each unit of cubic volume, weight, or board-measure is as valuable as all others. Even the board-measure log rules do not perfectly indicate true net value. All that they are intended to show is that the sawing waste that comes from converting round logs into square-edged boards is less in large logs than in small ones. They do not otherwise reflect the higher handling costs of small trees, except perhaps to the extent that inventions, such as the Doyle log rule which discounts small logs, may happen to do so accidentally. Even after wood is converted into flat boards, it is necessary to recognize that a board foot of a certain grade is usually worth more in a wide board than in a narrow one.

It is very important to make a clear distinction between the yield of forests and their production. **Yield** is the amount that is actually harvested or could be harvested. **Production** is more difficult to determine; it is the amount deposited by growth whether or not it is harvestable. Foresters reliably observed several centuries ago that thinning could increase the yield of usable wood from stands. However, the total production is ordinarily decreased. Some of the data about production after thinning are subject to large variations because of the inherent variability in productivity within tree species and in the plots of ground on which their growth is measured. It is also difficult to measure production precisely. Much confusion has arisen from attempts to measure production in terms of merchantable or quasi-merchantable cubic volume. These parameters approximate yield better than they do for production, and the diameter limits used in their definition are seldom standardized enough to compare results effectively.

If total production is measured in terms of tonnage of dry matter, there are extremes of stand density at which production would suffer. If the trees being measured did not fully occupy the growing space, their production would clearly be less than if they did fully occupy it. Some other vegetation that was not counted would tend to fill any unused space; its production, if counted, might partially offset the production deficiency of the trees.

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

If the stand density is very high, there are some instances in which total production is diminished. This happens when a large proportion of the fixed amount of stand foliage goes to support the respiration of such a large amount of living and consuming tissue that the surplus available to form new tissues, including wood, is reduced.

There are also cases in climates conducive to heavy accumulation of undecomposed organic matter in which thinning can speed decomposition and nutrient cycling enough to cause real increases in production. Some trees, even those of a given species, are inherently more productive than others, and thus stand production could theoretically be increased if such trees were favored in thinnings.

Otherwise, it appears that the thinning of ordinary stands will decrease rather than increase the kind of gross, total production that counts all organic materials in the stand, including the trees that died during stand development. If yield and production were indeed equivalent and everything that the stand produced could be harvested, it would be logical to confine thinning to the salvage of suppressed trees just before they died. The vacancies in the growing space left by heavier thinning, regardless of how small or temporary they may be, usually seem to cause uncompensated decreases in true total production.

It is economically impossible to turn all production into yield. Therefore, it is practical to consider how variations in stand density induced by thinning can affect production in terms of total cubic volume of stemwood or of potentially merchantable wood. However, it is clear that thinning can produce increases in merchantable volumes when desired tree dimensions for the product to be produced are increased (Fig. 22.1). But this departure from scientific measurement units, such as total dry matter, opens a Pandora's box full of product measurement units that differ in so many large or subtle ways that they can cause a good deal of confusion when making comparisons across regions and markets.

Almost any mode of measuring cubic volume of wood involves some restrictive choice of the smallest stem diameter or of the kind of stem material that will be counted. Total cubic volume is customarily taken to be all the wood in the central main stem from tip to groundlevel; this parameter is one for which bark is specifically included or excluded. It is reasonably well defined for most conifers and some hardwood species that have excurrent branching and single central stems. However, it involves a concept that is difficult to apply to species with decurrent branching and single stems that fork far below the tip of the crown. Even in excurrent branched trees, the so-called total volume does not include the wood of the small lateral branches or roots.

Merchantable cubic volume can be defined only in terms of some specification of the smallest diameter or other characteristic of stem components regarded as merchantable or, as potentially merchantable. Usually, the restriction is some minimum diameter, but sometimes it is the lowest point on the main stem where it forks or where large branches prevent utilization. Bark may or may not be included. Most European observations involve a diameter limit of 7 cm (2.75 in) including bark and branches, but American specifications vary greatly. Usually, whole trees that are below a certain diameter at breast height (DBH) are excluded.

The practical reasons for setting such restrictions are obvious, but they are probably also part of the source for the conflicting evidence about the relationship between stand density and production. The greater the stand density is, the slower the diameter growth of all stem components is, including branches. Therefore, the

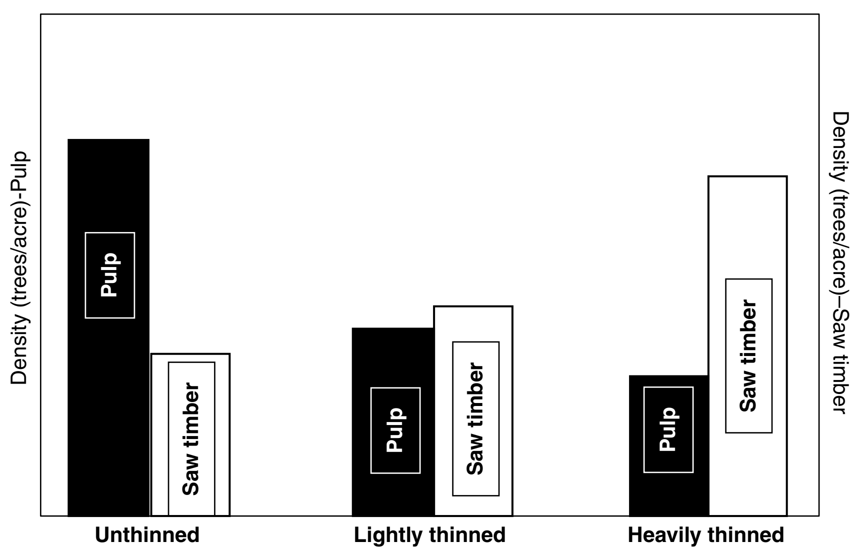


Figure 22.1 A depiction of the effect of thinning on product distributions, comparing unthinned, lightly thinned, and heavily thinned loblolly pine stands of the same age, 20 years after treatment in the southern US. "Pulp" refers to trees 6 inches DBH to a 4-inch top; "Saw timber" refers to trees greater than 12 inches DBH with at least 16 clear feet of bole. *Source:* Adapted from Virginia Tech University Loblolly Pine Growth and Yield Cooperative.

denser a stand is, the smaller the proportion of the total amount of wood that is included in merchantable cubic volume. When production is assessed in such terms, it often appears to be higher at moderate levels of stand density, such as those left by thinning, than at higher stand densities. The larger the restrictive minimum diameter set on measured cubic volume is, the more accentuated the effect; it becomes even more pronounced if production is measured in the American board-foot unit. Although such practical mensurational adjustments have clouded the scientific study of controlling stand production, they have advantages in considering the technology of thinning, especially if the nature of their effects is recognized.

The Effect of Thinning on Stand Production

There are three alternative interpretations that have been proposed about the relationship between stand production in gross merchantable cubic volume after thinning, and density to which stands were reduced in thinning (Fig. 22.2). Stand density is expressed in basal area after thinning, and cubic volume includes stemwood to a minimum diameter of 4 in (10 cm). Production is expressed as gross periodic annual increment during periods of 5–15 years between thinnings. Gross production includes wood laid down on trees that died during the period; net production would ordinarily deduct the entire volume of such trees, and will be discussed later.

The first interpretation, **Alternative A**, is that production increases right up to the highest level of stand density that can be maintained in nature. Any vacancy in the growing space is counted as reducing total volume production. It might be good to digress here to point out that there is a long-standing procedure under which it is presumed that Alternative A is represented by a straight-line relationship. It has been common in North America to predict yield from adjustments of so-called normal yield tables. These tables are based on stand densities equal to, or only slightly less than, the highest ones attainable, but such densities are so uncommon as to be abnormal in the ordinary sense of the word. Predictions of yield are often made by the simple assumption that a stand that has 80% of the "normal" stand density will give 80% of the "normal" production. This assumption would be correct if 20% of the growing space of the stand were vacant and remained so throughout the rotation. Although most stands have some permanent vacancies, these tend to refill to some extent; therefore, the assumption of a straight-line relationship between stand density and production would generally lead to underestimates. Thinnings are supposed to be light enough that all vacancies soon fill up again. Alternative A would probably fit the relationship between total production of dry matter and stand density, except that production might decline at very high densities in grossly overcrowded stands.

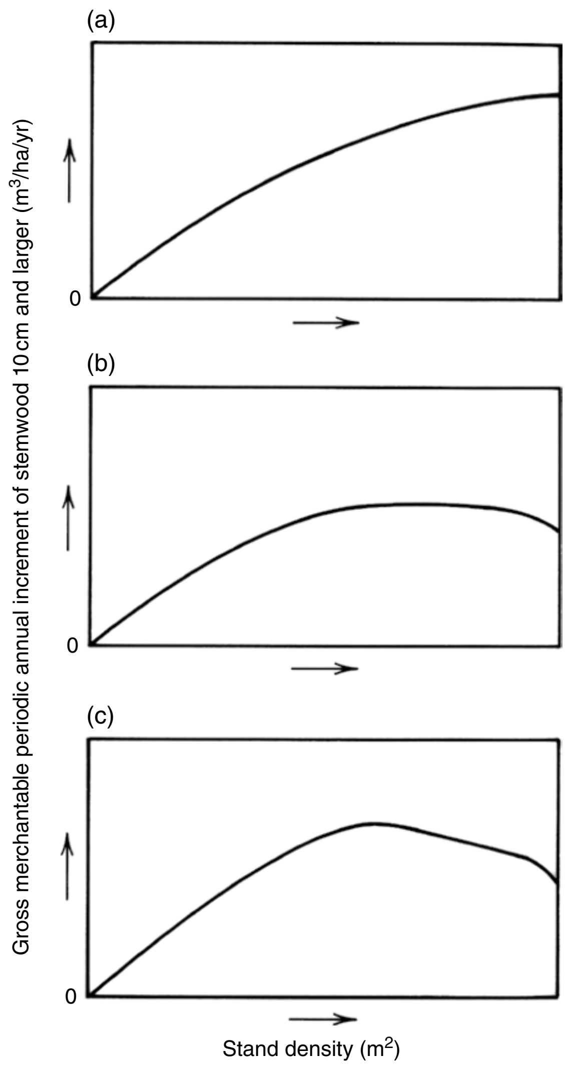


Figure 22.2 Graphs depicting three hypotheses about the effect of changes in stand density induced by thinning, on the production of merchantable stemwood in pure, even-aged stands, all of the same species, site quality, and age. See text for discussion. *Source:* Yale School of Forestry and Environmental Studies.

However, it is clear that when production is assessed in merchantable cubic volume, Alternative A fits only part of the cases.

The second, **Alternative B**, is that production remains constant and optimum over a wide range of stand density from some lowest level at which there is full occupancy of growing space, up to those levels at which excessive competition is postulated to restrict production. This interpretation received its greatest impetus from studies by Mar:Moller (1947, 1954) and others in Scandinavia. **Alternative C** assumes that production actually reaches an optimum and then declines. Alternatives B and C rest on the assumption that full occupancy of the growing space can exist at comparatively low levels of stand density.

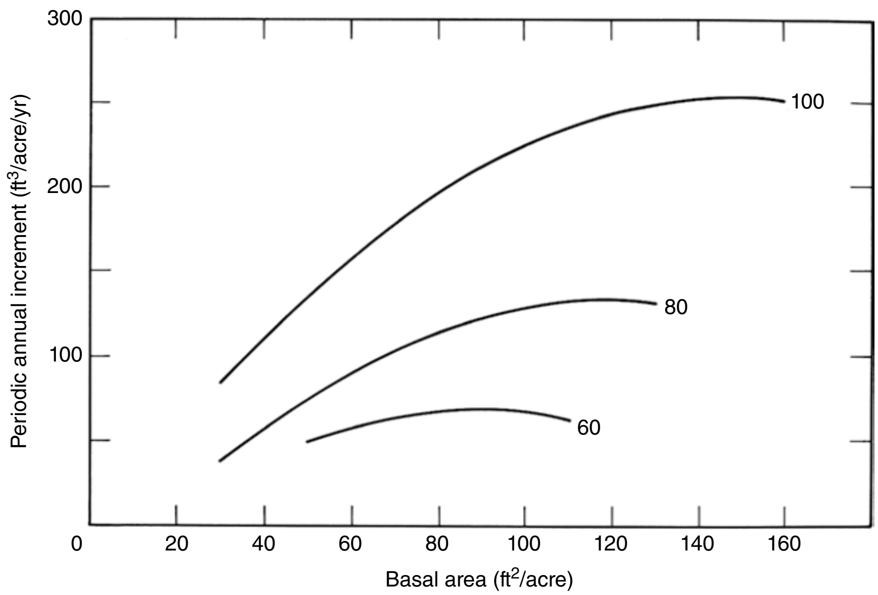


Figure 22.3 The 5-year periodic annual increment of merchantable cubic volume of stands of loblolly pine, averaging 40 years old, thinned to various levels of basal area. The stands were on sites of different quality in the southeastern US and these curves represent regression equations fitted to the experimental data by Nelson *et al.* (1961). These data suggest that on excellent, non-restrictive soils, the best cubic-volume production comes with light thinning or none (Alternative A of Fig. 22.2). However, on the more ordinary and common soils which are restrictive, optimum basal area gradually increases with age according to Alternative B or C early in stand development, but Alternative A best fits the final stages of a rotation. *Source:* Yale School of Forestry and Environmental Studies.

Differences in site quality may partly clarify the alternative interpretations illustrated in Fig. 22.2. Observations of many thinned stands of loblolly pine growing on different sites in the southeastern US show that production in thinned stands increases with increasing stand density on high-quality sites, but on more water-limited and poorer sites, the optimum is nearly the same over a wide range of stand densities (Nelson *et al.*, 1961) (Fig. 22.3). The data were fitted by statistical techniques that were not obviously biased in favor of any of the three alternatives. On the better sites, production increased to nearly the highest levels of basal area, much as Alternative A would suggest. However, on the poorer sites, Alternative B best fit the results.

It is quite possible that on the poorer sites, seasonal moisture deficiencies or other soil factors limit production more at high stand densities than at intermediate levels consistent with full or nearly full occupancy. On the better sites, production increases almost up to the limit set by the amount of light, because soil factors do not set much restriction on the amount or efficiency of foliage. If belowground production could be measured and were added to the total, the curves might have more similar shapes.

The analysis in Fig. 22.2 applies to production of merchantable cubic volume with quite small diameter limits. If the diameter limits were even smaller, Alternative A would probably approximate the truth better in more cases. However, if the minimum diameter limits were increased, the logic of Alternatives B and C and of thinning to ranges or points of moderate basal area would be strengthened. For example, if the American board-foot unit is used, which weights production in large stemwood more than that in small, then in many cases Alternative C, with rather heavy thinning, would presumably become most logical.

Part of the difference in interpretation between Alternatives A, B, and C results merely from the variability that would become obvious in the scatter of points representing the actual observations on which graphs such as those of Fig. 22.2 are based. Some of this variance is due to factors such as genetic differences, variation in site quality or stand density within experimental thinning plots, and observational errors, especially those involving the effect of taper on stem volume. In fact, the hypothesis of B may rest on nothing more than the fact that often there is no universally demonstrable upward or downward trend in total periodic annual increment with respect to moderate artificial decreases in stand density.

Even if Alternative B were incorrect, its tacit acceptance would have the thought-provoking effect of focusing attention on the thinning considerations that can be important regardless of what their effect on production of total cubic volume might be. If decades of study have produced so much contradictory evidence, foresters are entitled to conclude that as long as stands remain nearly closed, the effect of stand density on production is not

large enough to represent an exclusive consideration in determining how to thin.

Understanding Fertilizer Effects on Stand Productivity and Thinning

Current studies by ecosystem ecologists are investigating changes in forest productivity across the globe in response to climate change, enhanced CO_2 production, and nitrogen deposition from pollution. The important question is: how does productivity change with respect to changing site quality? Evidence now strongly suggests that most forest sites are nitrogen-limited, even within enhanced CO_2 environments, and that can limit stand productivity (Norby *et al.*, 2010). However, with additional nitrogen deposition from pollution, temperate forest productivity increases (Finzi *et al.*, 2007; Janssens *et al.*, 2010). Studies have also shown that enhanced CO_2 conditions in the soil increase soil microbial activity and accelerate soil organic carbon decomposition, thus releasing nitrogen tied to soil organic matter that is normally unavailable. This extra nitrogen can sustain the long-term enhanced growth of stands, shifting sequestered carbon from belowground to the living vegetation aboveground (Drake *et al.*, 2011). This is all background information that can relate to fertilization of forest stands and its interacting effects on thinning.

Actual experimental fertilization and thinning trials on loblolly pine that have been done throughout the southern US have demonstrated that stand productivity can be increased primarily by fertilization. Studies of 15-year-old loblolly pine plantations throughout the south by Jokela, Dougherty, and Martin (2004) have demonstrated a two- to three-fold increase in stemwood biomass with response to fertilizer and weed control. The most limiting nutrient that promotes the greatest growth response on these soils is phosphorus. The most intensive fertilizer applications with weed control and irrigation raised the basal area carrying capacity of 15-year-old loblolly pine from approximately 130–150 ft^2/acre (30–35 m^2/ha) to 195–210 ft^2/acre (45–48 m^2/ha) (Jokela, Dougherty, and Martin, 2004). However, the greatest individual tree diameter growth rates are from a combination of thinning and fertilization.

Growth and Yield

One of the primary objectives of thinning is to manage the production of wood by individual trees and the aggregated yield of the forest stand. As unmanaged stands develop, the growing space on the site is reallocated to different trees mostly as a result of competition. Thinning is the direct intervention in this reallocation process by eliminating some individuals and thus adding to the competitive strength of other individuals. Removing weak small tree competitors will have little effect on the overall growth of the stand. Removing large trees will shift growing space to weak competitors that will not immediately, if ever, be able to use the additional growth factors efficiently. Removing large trees thus reduces growth, resulting in lower yields over any fixed period of time. In other words, yield is regulated by thinning certain trees out of a stand and shifting growth to other trees.

Parameters of Stand Density or Stocking

Thinning is the direct reduction in the number of trees in the stand. It is necessary to consider first the relationship between the number of trees in the stand and yield, before the effects of thinning can become obvious. Growth is determined by the amount of foliage in the stand, but this is very difficult to measure. Many other measures are used to relate the foliage and the number of trees over which it is distributed.

The general term **stand density** is a measure of the amount of tree vegetation on a unit of land area. It can be the number of trees or the amount of basal area, wood volume, leaf cover, or any of a variety of less common parameters (West, 1983). **Stocking** is the proportion that any such measure of stand density bears to any of a wide variety of norms expressed in the same units and chosen for differing purposes. Density tells what is in the stand, and stocking tells how this density relates to a forester's notion of what ought to be, and usually in terms of percentages. For example, full stocking might be the basal area of trees larger than 10 in DBH/acre (63 cm DBH/ha) that was deemed necessary to maximize the production of sawn boards. A thinning schedule is a guide to what stocking should be at each stage of development, expressed as some kind of stand density.

No parameter of stand density has yet been devised that would define a series of thinnings that met any plausible set of objectives, if held constant after each thinning of a whole rotation. Many of these parameters can be used to quantify stand density or stocking in thinning schedules, but neither they nor any other form of simple mathematical magic seem able to define a schedule by themselves. It may help to consider the utility of each of these parameters as measures of density or stocking.

The simplest parameter of all is **number of trees** per unit area. This takes no account of either the sizes of the trees or the space they occupy. However, there is no fundamental reason why a thinning schedule could not be presented in these terms for a given species and site quality, if it had already been developed in terms of more meaningful units. Such a schedule would have to be adhered to rigidly because the trees would develop sizes different from those contemplated if there were significant departures from the program.

Basal area per unit of land is by far the most commonly used parameter, although there is probably more tradition than biological reason for this. Its main virtue is that it is a kind of integrated expression of numbers of

trees and their sizes. It was originally devised not so much as a parameter of stand density but as a crude indicator of cubic volume of stemwood. Because it measures the cross-sectional area of wood, it has no direct biological significance to the current stand structure. However, the basal area of a tree is fairly well correlated with the cross-sectional area of the crown. This means that if 25% of the basal area of a fully closed stand was removed, approximately 25% of the crown-level growing space would be made vacant.

It is quite easy to measure basal area per unit area by various point-sampling techniques. However, there is seldom any virtue in continually thinning back to some constant basal area, even though it often seems convenient to think so. It does make some sense to reduce the basal area by some percentage and then let it grow to a level higher than existed previously before thinning again.

Theoretically, the cubic volume of stemwood per unit area should be a better indicator than basal area of the amount of foliage per acre (hectare), but it is more difficult to determine, and there is no indication that the refinement would help. Because it is weighted by tree diameter, the board-foot volume is a good way to assess the results of thinning programs, but for the same reason it would not be a good parameter for expressing them.

There is strong evidence that good correlations exist between the **cross-sections of sapwood** and the amount of foliage on a tree (Waring *et al.*, 1977) (see discussion in Chapter 17). This surrogate parameter for foliage is difficult to use for a thinning guideline except in experimental situations. All specific allometric relationships between tree parts depend on the individual growing situation of a tree. For example, the stem height for a given correlation depends on the amount of butt-swell that can be attributed to wind sway. However, like all surrogate measures, sapwood cross-sectional area is very useful conceptually and can be used within stands to compare foliar amounts of different trees. It is a difficult measure to determine because increment borings need to be made in the trees and the sapwood area must be identified.

The amount of stem or **bole surface** of trees on an acre or hectare has the virtue of approximating the amount of growing and respiring meristematic or non-photosynthetic surface of the aboveground portion of the stand. If the amount of foliage that a stand of given species and site can produce is fixed, it would seem that the average diameter growth of the trees could be predicted by knowing how much bole surface area was linked to that foliage.

One useful index of bole surface per unit area is the **sum of the diameters** of trees. This is because bole surface is the sum of the products of circumferences and heights of tree stems modified by some function of stem taper. If the sweeping assumption is that the trees of an even-aged stand do not differ in height or taper, and note that *pi* is a constant too, then the sum of diameters becomes the chief variable function of bole surface. In this same way, it can be deduced that basal area could be changed to the sum of the squares of the diameters and it would get just as good a surrogate for stem volume per unit area. As far as the present purpose is concerned, much analysis has been done in terms of basal area but little in terms of bole area.

One particular difficulty lurks behind the use of DBH in assessments of stand density or growth. The problem is that trees are taller than people, and breast height usually falls in the zone of the butt-swell where the effects of fast or slow growth of whole trees are greatly exaggerated. This point is discussed in Chapter 17 (see Fig. 17.4). What this means is that one unit of basal area stands for more crown area with a smallish tree, than does that unit in a large dominant tree within the same stand.

This problem could be solved, at least in research work, by measuring diameters higher up on the trees. In American observations, the best fixed point would be at 17.5 ft, the level at which inside-bark diameter is measured to determine Girard Form Class. This mode of quantifying stem taper has been used in constructing many volume tables (see Table 17.1).

Relationships between Numbers and Sizes of Trees

Studies of single-species plant populations of a variety of plants have shown a relationship between the maximum number of individuals that can occupy a site and the average size of the individuals. In these studies, the maximum number of plants of any given size that can exist on a site is correlated to the average biomass raised to the 3/2 power (Westoby, 1984); it is called the **self-thinning law**, or the **three-halves thinning law**. Many attempts have been made to quantify and apply this relationship to forest stands. The major problem is that it is difficult to measure and precisely know the living biomass of a tree. As well as being large, most of the tree is dead wood within the living sheath of the cambium. As a result, many surrogate variables for biomass are used, such as volume, basal area, and diameter; all are imperfect and somewhat imprecise.

All thinning schedules derived from this type of straight-line relationship between the average sizes of trees and their total numbers are based on the fact that trees die from self-thinning when stands are near the maximum density for a given tree size. This process of self-thinning is a general phenomenon for all stands. As suppressed trees die, the remaining trees can get bigger and usurp the growing space of those that died (Fig. 22.4).

The slope of the self-thinning relationship between stand density and tree size is the same for all species provided the stands are single-species and even-aged stands.

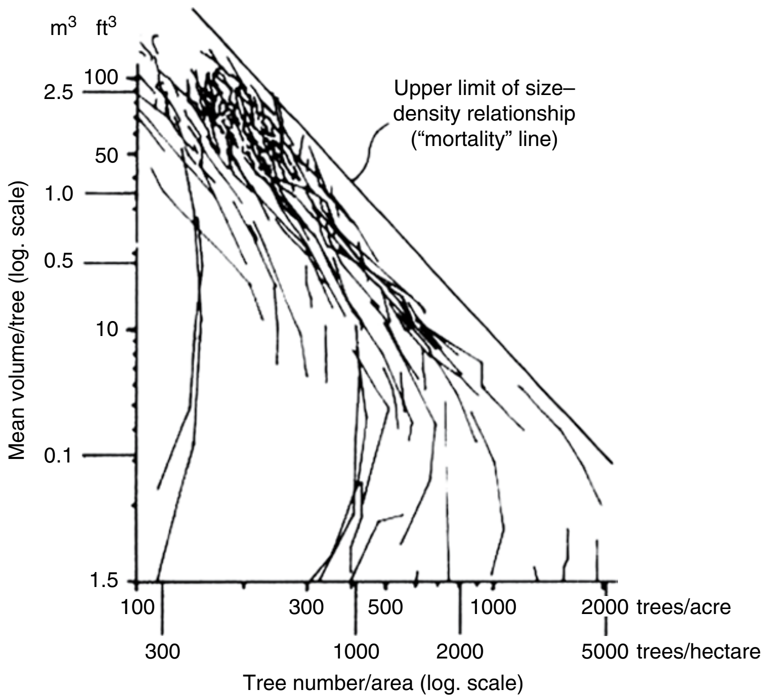


Figure 22.4 Changes in the average size of a tree over time for stands of different densities of even-aged Douglas-fir. Each line represents a stand that is tracked over time. As average tree size increases for a given stand, tree density numbers can remain approximately the same until the stand approaches the upper limit of the size–density relationship, after which stems decrease if tree size increases. *Source:* Adapted from Drew and Flewelling, 1979.

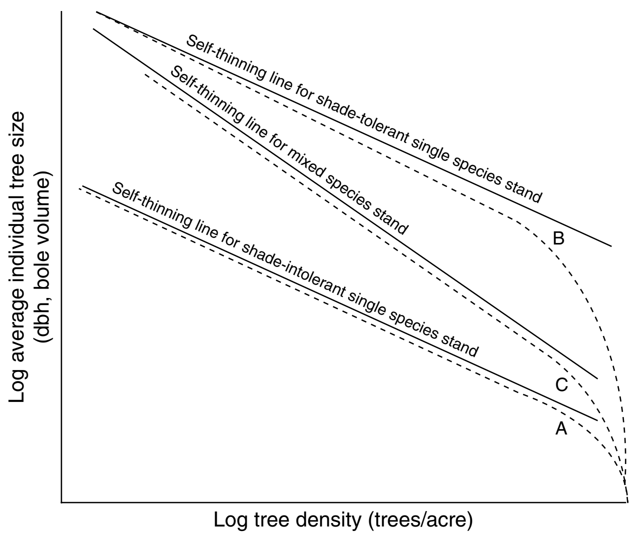


Figure 22.5 Size–density relationships for species with different shade tolerances. An illustration of the size–density trajectory of an initial stand composed of shade-intolerants (A); shade tolerants (B); and mostly of shade-intolerant pioneers with some shade-tolerants that, over successional time, changes to one dominated by shade-tolerant species (C). *Source:* Mark S. Ashton.

However, different species, given their inherent differences in shade tolerance, will have different upper limits to the size–density relationship. It is very conceivable that shade-tolerant species of a given size can pack in more individuals per unit area than shade-intolerant species (Fig. 22.5a). Although there is concrete evidence that this relationship holds in general, there is also evidence that there is considerable variation within species, across different site conditions, and among different species (Weller, 1987; Zeide, 1987).

For a stand that is uneven aged (multiple aged or all aged) or is mixed species, the relationship does not hold well. For mixed even-aged stands, it is conceivable to imagine that the size–density relationship changes gradually from one that initially develops along the self-thinning maximum for shade-intolerants within the mixture, and with their demise, moves upwards and across to a maximum for the shade-tolerants that eventually remain (Fig. 22.5).

Modeling Growth and Yield

Many attempts have been made to refine thinning schedules by simplifying the stand growth processes and explicitly including time. The simplest approach is a yield table that indicates the yield of stands at different ages on different sites. These tables are constructed by measuring stands of many different ages. Because not every age is equally represented, it is usually necessary to mathematically determine the yield for some ages to fill in the table. Different mathematical techniques can be used, but all represent some form of interpolation. The yields are assumed to be for fully stocked stands; stands less than fully stocked are simply reduced by a percent factor.

More sophisticated mathematical models can be constructed by using multiple regression equations (Clutter

et al., 1983; Vanclay and Skovsgaard, 1997; Weiskittel *et al.*, 2011). The purpose of the equations is to predict the growth of trees or stands on the basis of measurable factors that are alterable by thinning. In this procedure, as many factors as possible that might govern growth, the single dependent variables, are tested as independent variables in multi-term equations. Whatever equation explains the greatest amount of variation in growth (of tree or stand) is taken as the best quantification of the phenomenon. Among the independent stand variables that are commonly used are: age, basal area, numbers of trees, site index, average diameter, wood volumes, and various indices of stand density based on the aforementioned relationships between average DBH and numbers of trees.

When the goal is to explain the growth of individual trees, the variables often include the initial sizes of the trees themselves, site index, crown dimensions, distances to other trees, live-crown ratios, or parameters designed to quantify competitive effects. Each analysis is typically confined to data for some species in a particular locality and is designed to predict growth or yield rather than to explain the results.

This kind of analysis can be very useful in providing the basis for thinning schedules if it is done with due regard for both biological principles and those of statistical analysis. The results should not be used without critical appraisal and consideration of why the equations come out the way they do. The fact that multi-term equations have a superficial resemblance to those of physics does not mean that they explain everything.

If such analyses are set up so that the goal is to maximize the production of cubic volume per unit area, the equations will tend to indicate that thinning should be very light or not done at all. If the initial diameters of trees in even-aged, single-species stands are used as variables to explain the subsequent growth of the trees, this method will obscure the importance of other more fundamental variables. Such analysis will always show that the trees that have grown the best in the past are likely to continue to grow the best in the near future. The factors that caused the tree to grow well are obscured. The resulting equation is mostly an extrapolation of the past. These analyses are important because they remove any subjective bias of the observer, but they need to be interpreted carefully (Vanclay and Skovsgaard, 1997). Many dependent variables are not truly independent of each other, and the data used in the analysis are not well balanced because of these interactions. All applications of model results to combinations of conditions that did not exist in the original data must be made with great caution.

Sometimes the equations developed by multiple regression can be used to create computer simulation models. The equations are used to iteratively increment tree size; after each incremental increase, the larger tree size is run through the equation to increase tree size again (Pretzsch, 2009; Weiskittel *et al.*, 2011). It is important to remember that simple repetition of the equations will result in errors being compounded; trees that grow too fast in the simulation will continue to grow faster. Random effects are often added to the regression equations to approximate natural variation in basic growth rates (Stage, 1973; Pretzsch, 2009; Weiskittel *et al.*, 2011).

Regression-type simulation models can be developed for whole stands or for individual trees. In the latter case, the stand yields are determined by summing the individual trees. Another modeling approach is to grow each tree by calculating the effects of physiological processes and then determining the effects of competition between adjacent trees. These models can be either independent of tree location (Shugart and West, 1980; Vanclay and Skovsgaard, 1997; Pretzsch, 2009) and competitive effects between trees averaged, or individual crown growth can be simulated in location-dependent models (Mitchell, 1975; Vanclay and Skovsgaard, 1997; Pretzsch, 2009). A great number of computer simulation models exist. Each model has characteristics that make it appropriate for certain management questions in a given situation. It is important to determine which model is based on the appropriate assumptions for the problem at hand, rather than trying to rank models in general and having a “favorite” for all questions in all situations.

Additional Ideas on Growth

Interspecific Variations in Production

Further reference in this chapter to values of dry-matter production will, unless otherwise specified, be in terms of net **mean annual increment** (MAI), at or near culmination age for aboveground materials, including leaves of the current year, in metric tons per hectare per year. A metric ton is 1000 kg, and one metric ton per hectare is equal to 100 g/m^2, or 0.446 English short tons of 2000 pounds each per acre.

Clearly, some species produce more than others even when the site factors are the same. Evergreen species are basically more efficient than deciduous species because they use their investment in a year’s production of foliage for more than 1 year. Their foliage can also start photosynthesis whenever light, water, and temperature are favorable without any delay while new leaves form. In fact, in some regions such as the coastal Pacific Northwest, conifers may conduct a major portion of their annual photosynthesis during times when the hardwood trees are without leaves. In these areas, photosynthesis during the summer months is often restricted by drought.

Although conifers are often thought of as more productive than angiosperms, they are not inherently more

efficient. Broad-leaved evergreens, such as eucalypts, can be just as productive as evergreen conifers. However, many coniferous species have lighter wood and longer lengths of straight central stems than angiosperms. These attributes may make a conifer more productive than some hardwoods in terms of volume of usable stemwood, even if its biomass production is no greater.

The arrangements of branches within crowns and of leaves on twigs appear to cause some of the interspecific differences of photosynthetic production (Halle, Oldemann, and Tomlinson, 1978). For example, one highly efficient form of crown structure is similar to a candelabra, in which leaves are displayed in a single flat plane by wide-spreading branches. Although this form that is typified by some understory palms, has high photosynthetic efficiency, it is so weak structurally that the trees must remain small. Many trees growing in overtopped, low-light conditions adopt a single-plane type of foliar display. This crown shape has been called *monolayer* and is most efficient if light levels are below 50% of full light (Horn, 1971). Some early-successional species such as poplars exhibit rapid growth in youth because they have branch arrangements that allow them to develop closed sheaths of foliage in balloon-shaped crowns that cover the ground quickly. These species are called *multilayer* and are most efficient at high light levels. However, it is postulated that certain structural inefficiencies make it difficult for these species to sustain the early high rates of production.

Another highly efficient crown form is that in which substantial gaps exist between foliated branches. However, this structure is not conducive to swift occupancy of growing space. Stands of trees with this crown structure attain high, long-sustained amounts of **current annual increment** (CAI) only after the early stages of development. The mode of arrangement of leaves on twigs that is photosynthetically most efficient is the two-ranked one, in which the leaves do not shade one another. However, this arrangement is the least efficient in preventing the leaves from losing water and becoming overheated. Because there is no way that the open stomata of land plants can admit carbon dioxide for photosynthesis without letting water escape, high rates of photosynthesis have to be paid for with transpirational water loss (e.g., beech). There is now a growing body of evidence to show that mixtures of tree species are more productive than single species, precisely because different crown forms and their associated use efficiencies of light can be compatibly arranged. In a meta-analysis of 54 studies, Zhang, Chen, and Reich (2012) demonstrated that mixtures had an average of 24% higher productivity than single-species stands when species of compatible difference in shade tolerance were uniformly and evenly arranged amongst themselves.

Some species are adapted to drought periods because they close their stomata and can even lose their leaves and halt photosynthesis earlier during episodes of moisture stress. These species, called **drought avoiders**, avoid internal moisture stress that could cause the foliage to be permanently damaged, but do so at the expense of productivity because photosynthesis cannot continue if the stomata are closed. This adaptation to drought is one of several that reduce production but increase survival. On the other hand, **drought endurers** leave their stomata open and continue photosynthesis at the risk of suffering permanent wilt damage if the period of moisture stress is not short-lived.

Shade-tolerant species, whether evergreen or deciduous, are usually more productive than the intolerants (Givnish, 2002; Valadares and Niinemets, 2008). Actually, it is more accurate to think of shade tolerance as the result rather than the cause of this difference in photosynthetic efficiency. The organs that confer efficiency are leaves that can manufacture much sugar and also live at low light intensity. Species that have these leaves have more of them and also deeper crowns than the less efficient species. Perhaps because they have more leaves in the lower and cooler parts of the crown canopy, shade-tolerant species do not use such a high proportion of their gross photosynthate in respiration (Assmann, 1970; Valadares and Niinemets, 2008).

Species with dark-green leaves, denoting high chlorophyll content, tend to be relatively efficient. Another useful criterion is the leaf area index, which is the number of layers of leaf surface above each point on the ground. Values of this index vary from 3 to 12 in closed stands but are ordinarily about 5 (Waring, Newman, and Bell, 1981).

In a classic study by Ovington and colleagues, interspecific variation among species showed estimates of gross MAI (exclusive of roots but including current leaf production and material previously removed in thinnings) for stands of 40–47 years, at or near peak MAI, on comparable soils in the favorable climate of England (Ovington, 1957; Ovington and Pearsall, 1956). *Castanea sativa* and *Quercus robur*, deciduous species of moderate shade tolerance, had MAIs of 1.51–1.54 tons/acre (3.8–3.9 metric tons/ha/yr), respectively, and the MAI of *Fagus sylvatica*, a very tolerant hardwood, was 1.9 tons (4.9 metric tons). The evergreen conifers were more productive: *Pinus sylvestris*, 3.2 (8.0); *Pinus nigra*, 3.9 (9.7); *Pseudotsuga menziesii*, 3.9 (9.9); and *Picea abies*, 3.9 tons/acre/yr (9.9 metric tons/ha/yr). *Larix decidua*, a deciduous conifer, had a rate of 2.7 tons (6.7 metric tons), intermediate between the hardwoods and evergreen conifers. Data from other parts of Britain indicated that even higher rates than those of spruce and Douglas-fir are achieved by very tolerant conifers such as redwood,

the hemlocks, and true firs. Intolerant pioneer hardwoods such as *Betula alba* produced at lower rates than those of chestnut and oak. The yield of moderately intensive mixed agriculture in the same locality was 1.8 tons/acre/yr (4.5 metric tons/ha/yr).

A combination of intuition and data suggest that the highest production rates are in the evergreen tropical rainforest, where site factors are unfavorable to photosynthesis only at night. Annual production rates are at least 3.2 tons (8 metric tons) and possibly as much as 8.0 or 11.9 tons/acre (20 or 30 metric tons/ha). The high temperatures also induce such profligate respiration that the production rates are not clearly higher than those of the most favorable parts of the temperate zone. Studies show that the range of productivities across soil types is larger than that across temperature regimes, making this comparison very difficult.

The highest proven rates of production are for evergreen species in limited areas of wet, mild, strongly maritime climates at middle latitudes. One of the highest known values of CAI is 12.0 tons/acre (30.7 metric tons/ha) in a stand of western hemlock and Sitka spruce at an effective age of 21 years on the Oregon coast (Fujimori, 1971). The MAI was 3.6 tons/acre (9.2 metric tons/ha) and might culminate at about 8 (20 metric) some decades into the future. Such favored mid-latitude areas include the coastal fringe of western North America, parts of western Europe, southern Japan, and certain coastal areas in the strongly oceanic climate of the southern hemisphere. If the rainfall is sufficient and the soil favorable, the equable maritime climates of these areas provide very long growing seasons without the high temperatures that stimulate rapid respiration. Production rates approximating 6.0 tons/acre (15 metric tons/ha) have been observed with shade-tolerant conifers, evergreen oaks of southern Japan, and radiata pine in New Zealand (Cannell, 1982).

Most of the world's forests grow under less favorable conditions. In widely varying degrees, production is reduced by seasonal moisture restriction, which in some regions can exist at any latitude. These are periods when low temperature immobilizes water, and there are deficiencies of soil oxygen induced by excess water, low light intensity at high latitudes, or excessive respiration from high temperatures. However, the production rates of the poorest vegetation that might plausibly be called forest are not less than 0.4 ton/acre/yr (1 ton/ha/yr).

Observed production rates vary so much within species and genera because of site variations that it is risky to assign numerical values to any of them. The total production of a given species on a poor site is commonly only a half or a third of that on the best. In general, the greater the tolerance is for shade, the higher is the total production, although the trees may be slow to achieve such rates. The true firs are among the most productive of the conifers, yet the peak rates of aboveground MAI can range from 6.8 tons/acre (17 tons/ha) in Britain down to a tenth of that on the wettest sites where balsam fir will grow in eastern North America.

The two- and three-needled or hard pines which are so often grown for timber are generally not as productive of dry matter as the more shade-tolerant conifers. Many observations suggest maximum values of MAI around 2.4 tons/acre (6 tons/hectare). However, these species are most commonly grown on sites where there are significant seasonal moisture deficiencies. On better sites in parts of the southern hemisphere, production rates of Monterey pine and other pines can often be 4.8 tons/acre (12 tons/ha) or as high as 6.8 (17 metric) in the case of New Zealand. Thus, site factors can be as important as foliar efficiency.

It has sometimes seemed plausible that very fast-growing pioneer species or stands of coppice shoots grown on short rotations might sustain remarkably high values of MAI in terms of dry tonnage. The culmination of CAI for these species does come very early. However, such values of peak MAI that can be found, are generally less than those of species with slower rates of juvenile growth in height on the same sites. The high respiration rates of these species may offset the rapid gross photosynthesis associated with quick juvenile growth.

The culmination of MAI in terms of aboveground dry-matter production for a given species and situation, does not appear to come at ages much less than those of the peak values of MAI for total cubic volume of stemwood. This should not be surprising because stemwood accounts for a high proportion of the aboveground dry matter that accumulates in stands of trees.

Studies of total production tell a great deal about the fundamental biological factors controlling forest production and the tremendous role it plays in matters such as world budgets of energy and carbon. They also show the tantalizing possibilities of any technology that might enable closer utilization of the massive production of organic matter by forests. However, most use of wood is confined to those parts of tree stems that are large enough to be handled economically. One key problem of timber-production silviculture is manipulating this production so that as much of it as possible is channeled into usable stem sizes commonly defined in terms of merchantable cubic and board-foot volume.

There is ample evidence showing that levels of optimum basal area tend to be greater for shade-tolerant species than for intolerant ones and greater for evergreens than for deciduous species. The more efficient the foliage of a species is, the greater not only the production is but also the amount of growing meristematic tissue that can be nourished efficiently. The approximate ranges of appropriate residual basal area after thinning

for middle-aged stands of these four categories of species may be tentatively stated as follows:

	ft^2/acre	m^2/hectare
Tolerant evergreens	130–230	35–60
Intolerant evergreens	80–130	18–35
Tolerant deciduous	70–160	16–37
Intolerant deciduous	50–80	12–18

It should not be inferred that the limits stated here are precise. The basis for the implication that the logical ranges are greater for tolerant than for intolerant species is weak, although stands of shade-tolerant species do seem to be more flexible in their response to thinning than those of intolerant species.

Where differences in site quality are substantial, the logical basal area for stands of a given species would be less on a poor site than on a good site because the foliage per square meter is so much less. If the site is capable of supporting a stand with a closed canopy, the difference may be smaller than might be assumed because development progresses so much more slowly. The basal area left after thinning would be much less at comparable ages, but if residual basal area is allowed to increase with age, the differences at comparable heights would be small. However, in arid forest regions, such as those of parts of the interior ponderosa pine region, full closure of the root systems is possible with as little as 10% canopy cover. Ideas about levels of basal area appropriate to more humid forest regions would scarcely be applicable there.

Quantitative Thinning Guidelines

Density, Stocking, and Relative Density

There are three important measures that have been described to gauge response of trees and stands to treatments: (1) **stand density**, (2) **relative density**, and (3) **stocking**. Stand density is an absolute measure of tree occupancy per unit of land area. Measures of stand density include numbers of trees, basal area, biomass, and volume per unit area. Relative density is a measure of the actual stand density as compared to the maximum measured stand density that could occur on the site for a given mean tree size and stand age. Stocking is an indicator of growing space occupancy for a stand as compared to a baseline standard. Stocking indicators are usually measured as percentages of basal area, density, or crown competition.

These three measures and the relationships between them are the core to building any number and variety of thinning guidelines. They are the basis for stand density indices, stand density management diagrams, stocking indices, and crown competition factors. All thinning guidelines do have one generalization: they all relate the size of an individual in some way (crown size, DBH, tree volume) to the number of individuals per unit area (density of trees, basal area, total crown projection area) (Long and Smith, 1984). It can be dangerous to deduce “laws” from artificially constructed models that are at least once removed from the original data. In this case, however, it is probably safe to infer that these relationships do exist in crowded stands and have a biological basis. Because most of the diameter and volume of a tree is a reflection of past growth and not current status, parallel relationships do not exist between stands grown by thinning regimes that kept stand density away from the open-grown condition or that of overcrowding. Similarly, it is not clear that quantitative guidelines of this type should be consistent across thinning methods. The vigor of the trees left after thinning will determine how quickly the vacant growing space is reoccupied

There are two thinning guidelines that directly relate tree size to stand density. **Stand density indices** (SDIs) are the most direct form of guideline. Stand density management diagrams are more refined species-specific versions of an SDI. Both SDIs and density management diagrams are specifically developed for plantation systems or for single-species even-aged stands. The third protocol used for thinning is the use of stocking guidelines. Stocking guidelines are more general and are designed for even-aged mixed-species forests. Such forests now dominate lands that once had been cleared for agriculture and have now come back to second-growth forest (central hardwoods, Appalachian hardwoods), or forests that have been heavily cutover (northern hardwoods). Stocking guidelines are not nearly so precise because they cater to mixtures of trees that are all growing at different rates in intimate mixture.

Stand Density Index

The stand density index developed by Reineke (1933) is based on inverse straight-line relationships between the logarithms of (1) average DBH, and (2) numbers of trees per acre (Fig. 22.6). The index value is the number of trees for stands that have average DBH of 10 in (25 cm). This value becomes higher as the species is more shade tolerant (Table 22.1). This index is one of the easiest to use because it is not necessary to determine the tree volume (Box 22.1). The Reineke stand density index and other SDIs are most applicable to pure, even-aged stands. Such indices can guide thinning decisions by helping to determine the target number or trees per acre (hectare).

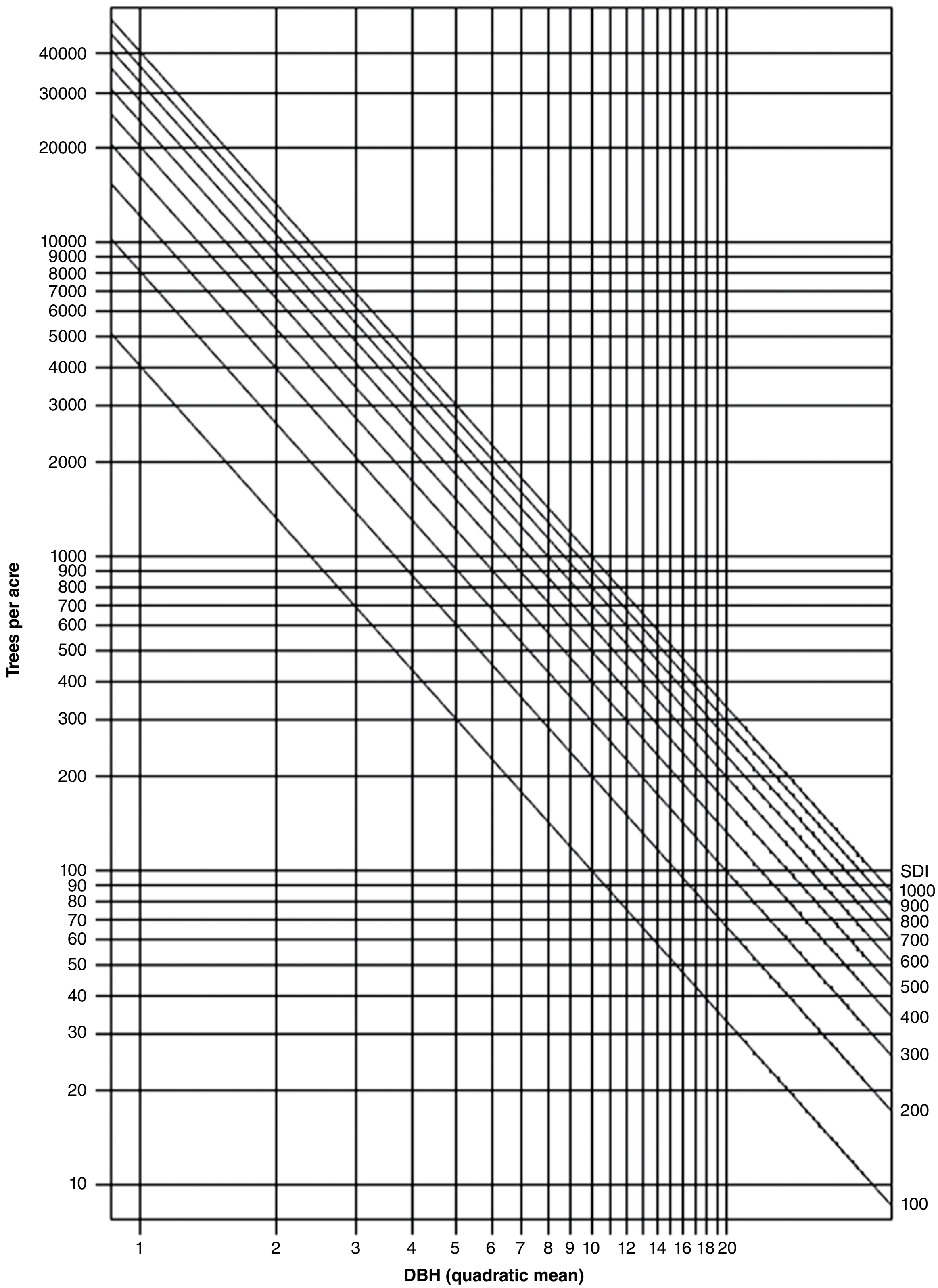


Figure 22.6 The Reineke Stand Density Index. *Source:* US Forest Service.

Table 22.1 Stand density indices (SDIs) for a range of shade-tolerant and -intolerant tree species. English units are number of 10-inch trees per acre. Metric units are number of 25.5-cm trees per hectare (CA, California; WA, Washington; OR, Oregon).

Species	Maximum SDI (English)	Maximum SDI (metric)	Source
White fir	830	2050	Reineke, 1933
Red fir	1000	2470	Reineke, 1933
Mixed conifer for CA	750	1850	Reineke, 1933
Douglas-fir for WA-OR	595	1470	Reineke, 1933
Douglas-fir for CA	600	1480	Reineke, 1933
Eucalyptus	490	1210	Reineke, 1933
Redwood	1000	2470	Reineke, 1933
Ponderosa pine	800	1980	Reineke, 1933
Loblolly pine	450	1110	Reineke, 1933
Longleaf pine	400	990	Reineke, 1933
Slash pine	400	990	Reineke, 1933
Shortleaf pine	400	990	Reineke, 1933
Upland oak	230	570	Schnur, 1937
Ponderosa pine	830	2050	Long, 1985
Lodgepole pine	690	1700	Long, 1985
Douglas-fir	587	1450	Long, 1985
Western hemlock	790	1950	Long, 1985
Ponderosa pine	450	1110	Long and Shaw, 2005

Source: Mark S. Ashton.

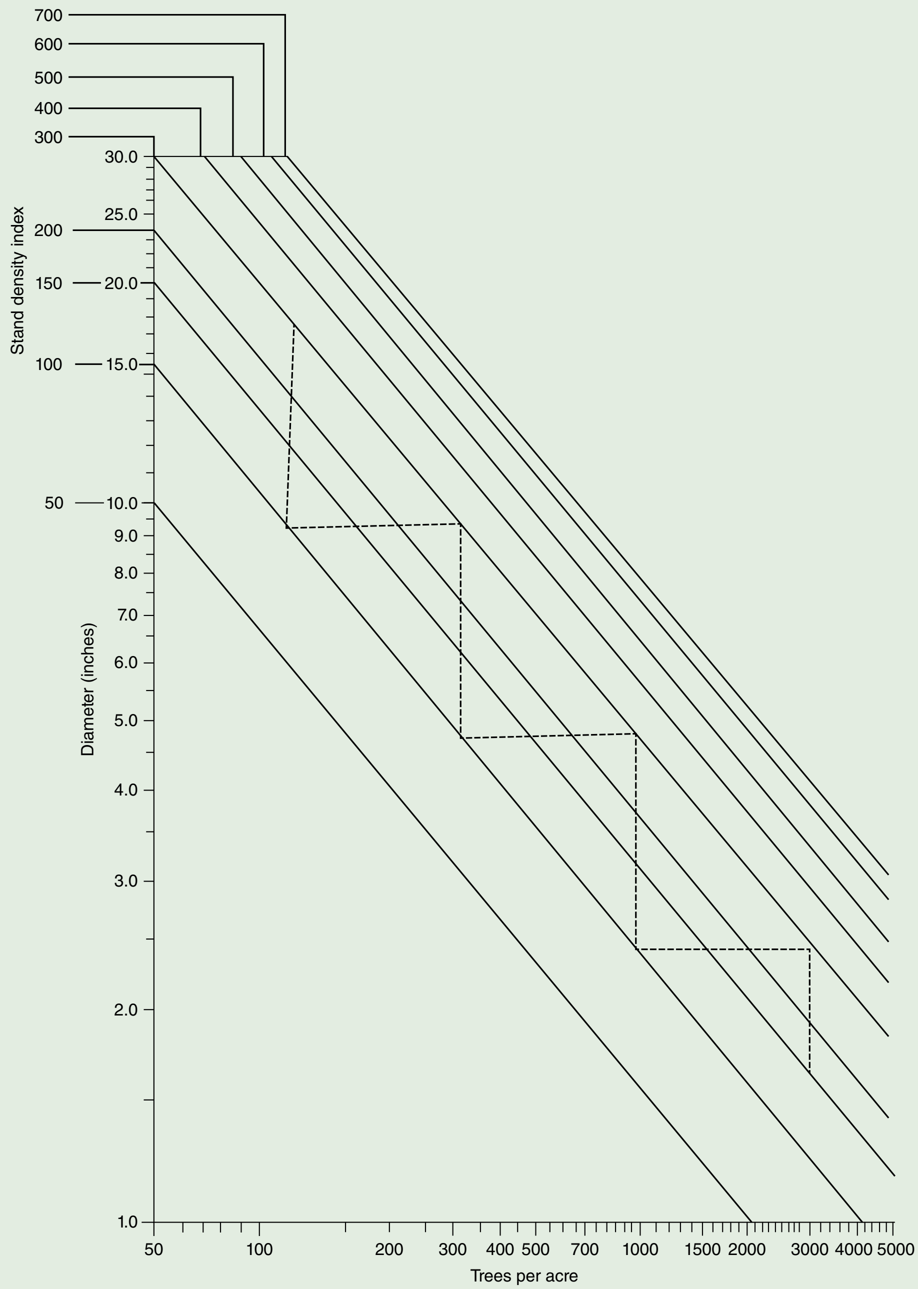
Box 22.1 How to use the Reineke's stand density index (SDI) (this example is in English units only).

In order to use the SDI on a stand, two pieces of information are needed: the quadratic mean diameter (not the arithmetic mean diameter), and the current number of trees per acre. These numbers are obtained by first taking a few fixed sample plots in the stand. After calculating these numbers, you can assess where the stand condition lies with respect to the known SDI for the tree species and the location (regional provenance) of the stand.

For example, your stand has a quadratic mean diameter of 2.5 in and 3000 trees/acre and you know that the stand density index for the species you have is 300 (Fig. 1). If you look at the trees/acre for a diameter of 2.5 inches, you can see that the stand is very close to the line for an SDI of 300. You should do some thinning, but how much? You decide that the next thinning should be done when the average diameter of the stand has pulpwood value. The SDI line for 300 tells you that a stand can have a precommercial thinning removing two stems to every one (2000 stems/acre), leaving 1000 stems which will then be free to grow to an average diameter of 5 in for a pulpwood thinning. After a pulpwood thinning, the first commercial sawtimber can be harvested when the stand is about 10 in, which should have about 300 trees/acre. This means you need to remove about 700 trees/acre for pulpwood when the trees reach 5 in DBH. Assuming that regular or uniform spacing in the stand is the goal, approximately 12 ft should be left between the crop trees to get 300 trees/acre. The crop-tree spacing can be estimated by taking the square root of the area in feet needed for each tree.

$$\text{Spacing in feet} = \sqrt{\frac{43560\,\text{ft / acre}}{\text{trees / acre}}}$$

Box 22.1 (Continued)



Box 22.1 Figure 1 A depiction of Reineke's stand density index with a thinning schedule to move the stand to a mean DBH of 12 in. The current stand has a mean DBH of 2.5 in and 3000 trees/acre with a series of thinning prescriptions to move the stand to 10 in DBH and 300 trees/acre. *Source:* Yale School of Forestry and Environmental Studies.

Stand Density Management Diagrams

A set of diagrams has been created to graphically illustrate measures of tree density and tree size over developmental time for a particular species. The relationships were originally developed in the 1960s by Japanese scholars for mono-specific crops of annuals (Drew and Flewelling, 1977). The diagram allows the users to position a stand within the context of the limits of the stand developmental process for the species. Thus, the user can assess where the stand lies in relation to minimum and maximum self-thinning conditions, zones of crown closure, and stand volume and yield. The diagrams can then allow the forester to project what treatments may be necessary to capture mortality and maximize dimensional product yield for their site condition and socio-economic circumstance. These **stand density**

management diagrams (SDMDs) have been developed for all the most important timber plantation trees of the world. Like stand density indices, they are appropriate for even-aged, single-species stands (Newtown, 1997). Because stand growth patterns can change from one region to another for many wide-ranging timber species (e.g., eastern white pine, lodgepole pine, Douglas-fir, and loblolly pine), SDMDs need to be developed for different climate and physiographic regions for a given species. In some cases, because spacing is critical in developing projected models of competition and growth, SDMDs have been developed separately for uniformly planted stands, and stands that are clumped in natural origin (see Box 22.2).

The relationship for Douglas-fir was first derived by Drew and Flewelling (1979) and is shown in Fig. 22.7. It is important to notice that a stand that starts at a certain stand density well below the maximum line will eventually reach the point of maximum density and trees will begin to die just because the individual trees grew in size. The relationship between the stand density and the maximum density that could occur at the same average tree size is referred to as the **relative density**. Thinning guidelines can be drawn up that indicate at what relative density thinning should take place, based on the products desired and experience with the species. In such a guideline, many light low thinnings will have a very little effect on the relative density of the stand because the average tree size will change little, although the density will decrease. Mortality will be captured by the harvest without providing increased growth to the codominants. Other measures of relative density have been developed based on other tree measures.

Stocking Diagrams

To develop a stocking diagram, rather than try to gauge where the self-thinning line is for a given species, the opposite part of the possible range of stand density can be measured, namely the open-grown tree (Gingrich, 1967, 1971). In this, it is postulated that the very lowest density to which a stand might logically be thinned is that in which each tree was left occupying the space that its crown could expand to cover if it were open-grown. The statistical relationships between the diameters and the numbers per acre (hectare) of such trees are determined for hypothetical stands that consisted of open-grown trees of uniform stem sizes that were just barely closed. The upper limit, beyond which stand density should not be allowed to increase, is defined by similar relationships between numbers and sizes of trees in fully stocked stands. The results are usually plotted on nomograms like that shown in Fig. 22.8 (see Box 22.3).

Box 22.2 How to use a stand density management diagram (SDMD) (this example is in metric units only).

To use an SDMD, one must first determine if such a diagram exists for the species and region in question. It is important to select the growth projections and SDMD for the correct region as growth can change within a species range. This example is for western hemlock in the southwest region of British Columbia. SDMDs can be developed and used for pure even-aged species stands for a particular region. SDMDs are useful for evaluating where your current stand conditions lie with respect to others, and for the design of a prescription for its future development given the yields and product dimensions desired.

Assume the stand is a pure, even-aged western hemlock stand in coastal British Columbia. An SDMD has been developed by the British Columbia Ministry of Forests (1997) (Fig. 1). To find the position of the stand condition under assessment on the diagram, fixed area plots need to be placed within the stand, and trees/ha, stand top-height, and quadratic mean stand, calculated. In this example, the stand under assessment has a 6 m top-height and has an average of 800 trees/ha. To predict the stand's future development, trace its growth development vertically upwards until it moves into the density range for maximizing current annual increment (CAI). This is the zone where the stand for that height and diameter will need to be thinned, if mortality is to be captured for a product. It is when the stand reaches a stand top height of 32 m tall and 35 cm DBH that it can be thinned if desired, taking the stand away from the zone of mortality and taking the stand back to about a density of 400 trees/ha and removing a volume of:

$$1.0\,\mathrm{m}^3 \text{ per tree} \times 400\,\text{trees/ha removed} = 400\,\mathrm{m}^3/\mathrm{ha}$$

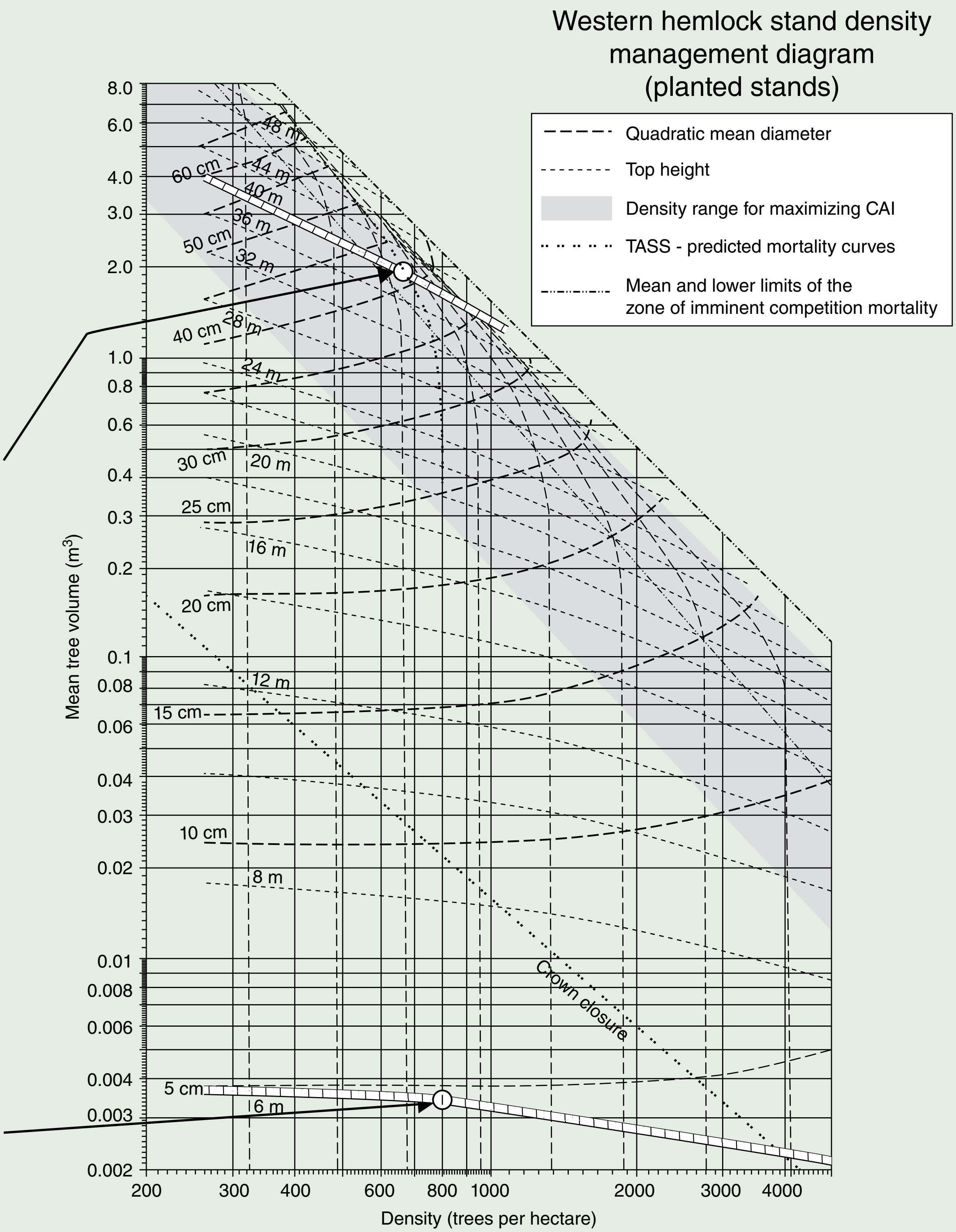
The next could be done when the stand has an average DBH of 55 cm and 4 m^3 per tree if so desired. If it is a clear felling with the objective of planting, the stand at that time would yield:

$$4.0\,\mathrm{m}^3 \text{ per tree} \times 400\,\text{trees/ha harvested} = 1600\,\mathrm{m}^3/\mathrm{ha}$$

If the stand was left to develop without any thinning and was to be clear felled when mortality started occurring, the quadratic mean DBH of a tree would be 42 cm, with a stand density of about 670 trees/ha each with a mean volume of 1.9 m^3. The predicted yield would be:

$$1.9\,\mathrm{m}^3 \text{ per tree} \times 670\,\text{trees/ha} = 1273\,\mathrm{m}^3/\mathrm{ha}.$$

Box 22.2 (Continued)



Box 22.2 Figure 1 Stand Density Management Diagram for western hemlock growing in coastal British Columbia. *Source:* British Columbia Ministry of Forests, 1997. Reproduced with permission from the Province of British Columbia.

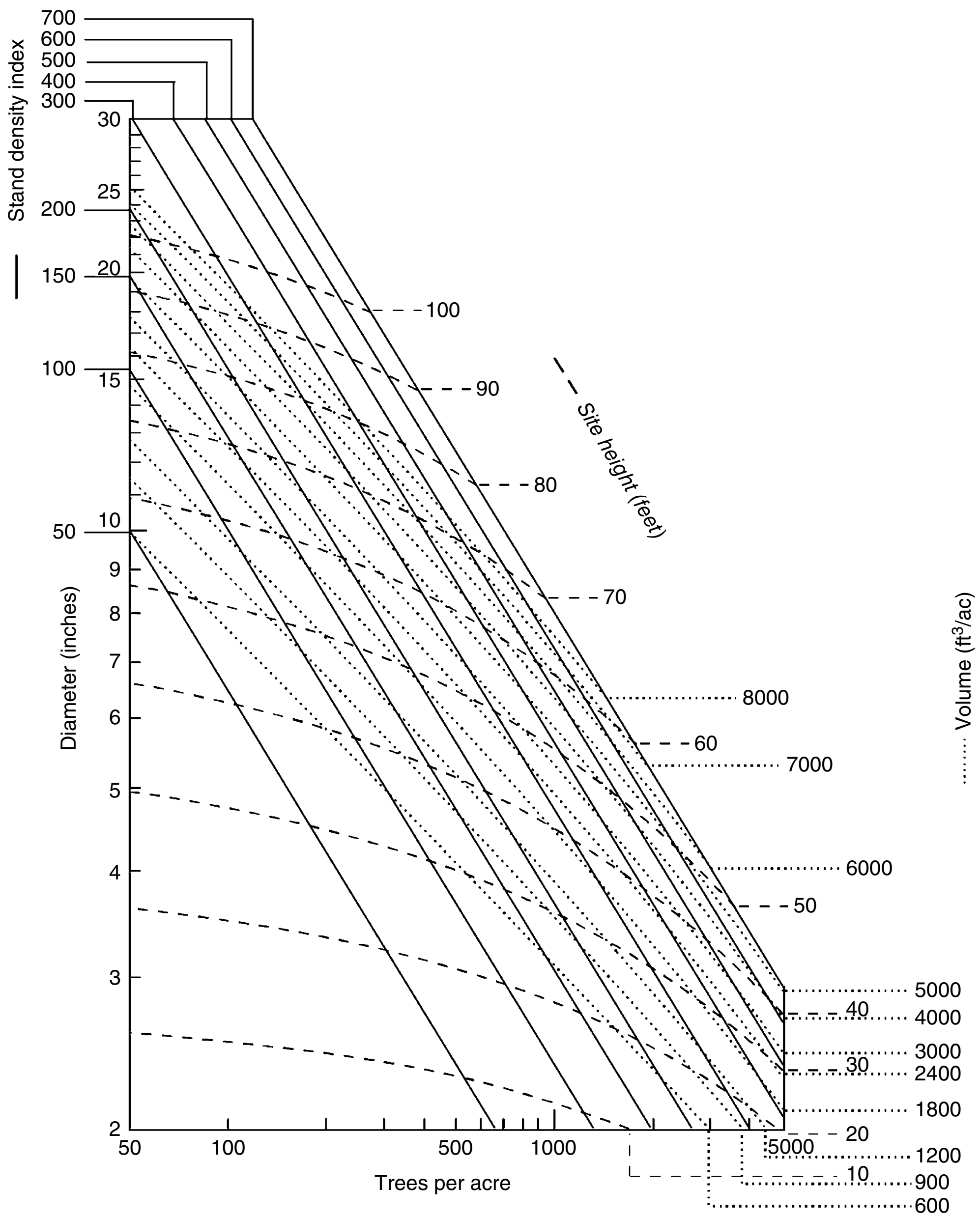
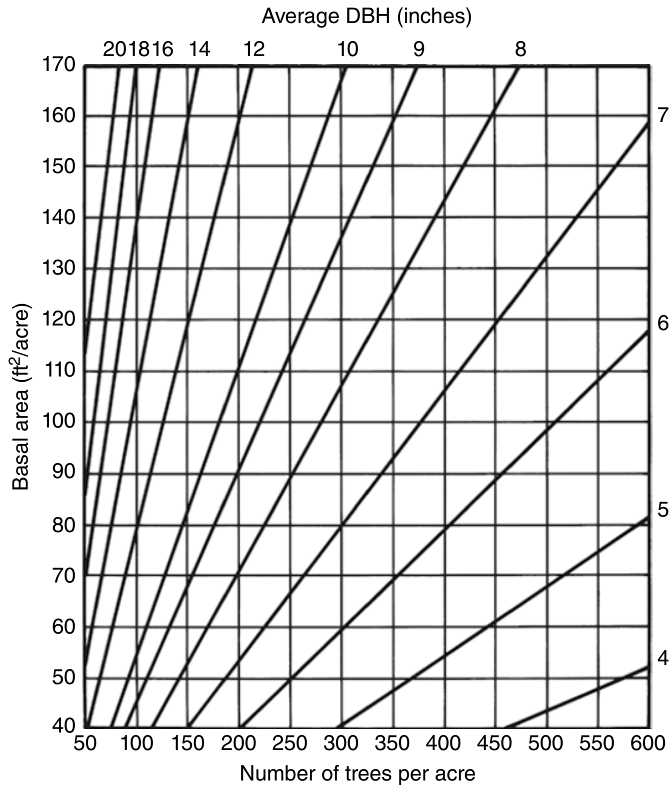


Figure 22.7 A stand density management diagram for lodgepole pine, showing the relationship between maximum average tree size (as measured by diameter in inches) and number of trees/acre. As trees get bigger, the growing space can be occupied by fewer trees. Relative density is defined as the number of trees that are actually in a stand, divided by the maximum number of trees of that average size that would exist. Depicted in the diagram are the limits of imminent mortality, volume (ft^3/acre), top height, and predicted trajectories of stands of differing densities with development. *Source:* Drawing by W. Lindquist, 2016, based on data from J.B. McCarter, J.N. Long (1986) *Western Journal of Applied Forestry*, 1986.

Crown Competition Factor

Crown competition factor (CCF) has been developed as another technique to evaluate growing space occupancy of trees (stocking). It can be used to both develop spacing guidelines at time of planting, and thinning guidelines. It is based on the relationship between crown size (crown width, crown projection area, crown volume) and tree diameter, and can be defined as the area available to the average tree in a stand compared to the maximum area used by an open-grown tree with the same diameter. It is best applied to even-aged stands that are of single species (plantations). To develop CCF for a tree species, widely spaced plantings can be measured annually for crown widths and stem diameters, and the

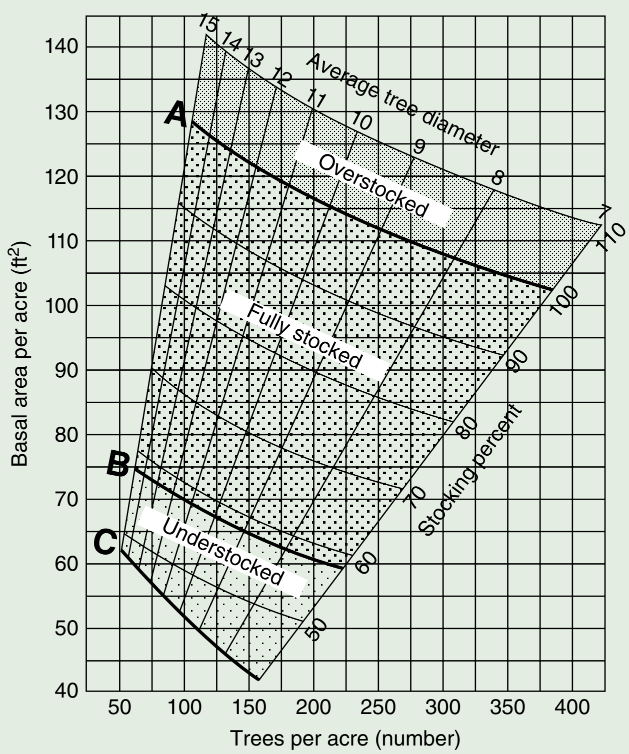
Figure 22.8 A nomogram for relating the average DBH of stands to basal area and numbers of trees per acre in the guidance of thinning schedules (in English units only). Note that the average DBH of a stand is, by convention, the quadratic mean or the DBH of the tree of average basal area and not the arithmetic mean. The largest trees in the stand would usually be considerably larger than the average tree. Almost any thinning schedule could be described on this diagram by a saw-toothed line along which the stand "moved" over time from right to left. However, there is nothing inherent in this diagram that tells what the schedule should be or how rapidly stands could be made to "move" across it. Stocking guidelines have been developed for most mixed-species hardwood stands by Gingrich (1967) for the central upland hardwood forest, and by Larsen *et al*. (2010) for the bottomland hardwood forest. *Source:* Yale School of Forestry and Environmental Studies.



Box 22.3 The Gingrich Stocking Diagram (this example is in English units only).

The Gingrich diagram was first published in 1967 (see Fig. 1). It is a nomogram illustrating the relationship between basal area per acre, trees per acre as a measure of density, and quadratic mean diameter. The C-line demarcates the lowest stocking that a stand can be at (understocked) and still grow to attain the B-line within 10 years assuming average site quality. The B-line is an estimated point at which the stand can be at full occupancy of growing space. The A-line is the minimum tree area line for a stand considered to be at full stocking that has never been thinned. A stand that is above the A-line is considered overstocked, where tree growth is slow and mortality is high. The area between the A- and B-lines is the range of stocking where trees can fully utilize the site.

Box 22.3 Figure 1 A stocking diagram for central hardwoods (Gingrich, 1967). To use the stocking diagram, plots need to be placed in the stand to estimate basal area and number of stems over 2 in DBH. It is best to use fixed-area plots of sufficient size and number to account for stand heterogeneity. Then knowing the basal area and tree density, and positioning this point on the diagram, the average tree diameter and stocking level can be interpreted. If the point is above the B-line, then follow the average tree diameter for your stand down to the B-line, and then follow the horizontal line across to read the basal area for the B-line for that diameter. Subtracting the basal area recorded for the stand from the basal area at the B-line for the stand at that diameter, gives the user an estimate of the allowable amount of basal area that can be cut in a thinning. *Source:* US Forest Service.



data are used to develop regressions predicting crown diameter/width from stem diameter. A table can then be constructed predicting the proportion of crown area occupying open space for a given stem diameter. This table can be used to develop spacing guidelines for tree plantings with the knowledge of the diameter that the tree will attain before reaching crown closure and imminent competition. Trees that are more closely spaced, at spacing purposely overstocked, can be used to determine stem diameter–crown size relationships under strong competition and can identify the upper limits of maximum stand growth at a higher CCF. Crown competition factor (CCF) is therefore an index of crown area for a given number of trees of a mean diameter; a CCF of 100 would be full occupancy where crowns of each and every tree were occupying every inch of growing space but there was no competition. If there was another stand of the same species and diameter, but there were twice the number of trees, the CCF would be 200.

Uneven-Aged Guidelines

Quantitative guidelines for all-aged systems have been described in detail under Chapter 13 (selection regeneration methods). Like quantitative guidelines for even-aged methods of management, uneven-aged guidelines rely on distribution patterns and relationships between size class and numbers of individuals. The most commonly used guideline is the ***q*-factor** where diameter distributions are converted to straight lines using the logarithm of numbers of trees for each size class. Selecting the shape (slope), the amount (basal area), and the largest diameter class the stand should attain, are the core factors to develop a guideline.

Alternative methods that more accurately gauge size-class distribution in relation to growing-space allocation have been developed by O'Hara and colleagues. These guidelines rely on measuring more direct relationships of amounts of the foliar area or crown areas of a tree to its basal area or diameter increment (O'Hara, 2002, 2014; O'Hara and Gersonde, 2004).

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Part 5

Silvicultural Considerations for Managing All Forests

All forests need to develop a silviculture that considers operational constraints, accommodates wildlife, restores or maintains forest health and resilience in relation to the unpredictable impacts of biotic and abiotic agents.

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23

Conservation Management Practices

Introduction

Conservation management practices (CMPs), also more commonly known as best management practices (BMPs), establish a framework for sound forest management. CMPs were initially designed to provide guidelines for maintaining water quality (Dykstra, Heinrich, and Harcharic, 1996; Aust and Blinn, 2004; Higman *et al.*, 2004), but the CMPs outlined here have been extended to promote the healthy functioning of forest ecosystems and to improve the aesthetic quality of forest operations when any kind of silvicultural prescription is implemented. They have been named CMPs because they more accurately reflect the minimum range of considerations that need to be taken into account when applying any kind of silvicultural treatment. They are not necessarily the "best," but they are the constraints that need to be considered when applying a prescription that is focused on implementing one or a mixture of objectives (i.e., timber production, water yield, early seral wildlife habitat) that will ensure conservation of the other values of a forest resource. Many state-level and province-level BMP manuals were originally designed only to protect water quality, and many are still restricted to that objective. The CMPs described here are not confined just to water issues, but to a diverse array of resource conservation values that need to be considered when silviculture is actually practiced.

Management Practices

There are two broad categories of management practices: (1) those done in the design phase, and (2) those done in the operational phase of silvicultural treatments. It should be kept in mind that these practices are intended to provide principles for good stewardship that should be incorporated into all silvicultural prescriptions. The actual application of these principles will always depend on the specific conditions of the area of forest being considered, especially where management practices have contradictory goals (e.g., the presence of slash with respect to wildlife or aesthetics). In many cases, the same practice may meet multiple objectives. In particular, many guidelines intended to protect water quality will also help to maintain the integrity and productivity of forest soils. Many studies have demonstrated the benefits of implementing CMPs at all times, even if only rudimentary silviculture is performed, as in the tropics (Briggs, Cormier, and Kimball, 1998; Schuler and Briggs, 2000). It is important to consult the sources listed at the end of this document for more details about the application of these practices. Many of these guides are at state or province level in North America, and provide much greater depth and site-specific particulars to the region of focus (e.g., Sevedbagheri, 1996; Georgia Forestry Commission, 2009; Colorado State Forestry Service, 2010; New York State DEC, 2011; Catanzaro, Fish, and Kittredge, 2013).

In this chapter, 10 conservation management practices are presented, which all silvicultural prescriptions should strive to include. They are listed below in the order described, and are logistical, legal, physical/operational, biological, and cultural.

1) Recognize and protect property boundaries, public roads, and trails (legal).
2) Develop methodical timber-marking procedures (logistical).
3) Carefully plan haul roads, skid trails, and landings (logistical).
4) Match logging machinery and operations to site and economics (logistical).
5) Identify and understand the properties of operable soils (physical).
6) Protect wetlands, permanent streams, and bodies of water (physical).
7) Avoid close utilization on certain sites to protect site productivity (biological).
8) Maintain structural and biological diversity (biological).
9) Preserve cultural legacies of land-use (cultural).
10) Maintain aesthetics (cultural).

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Recognize and Protect Property Boundaries, Public Roads, and Trails (Legal)

Property Boundaries

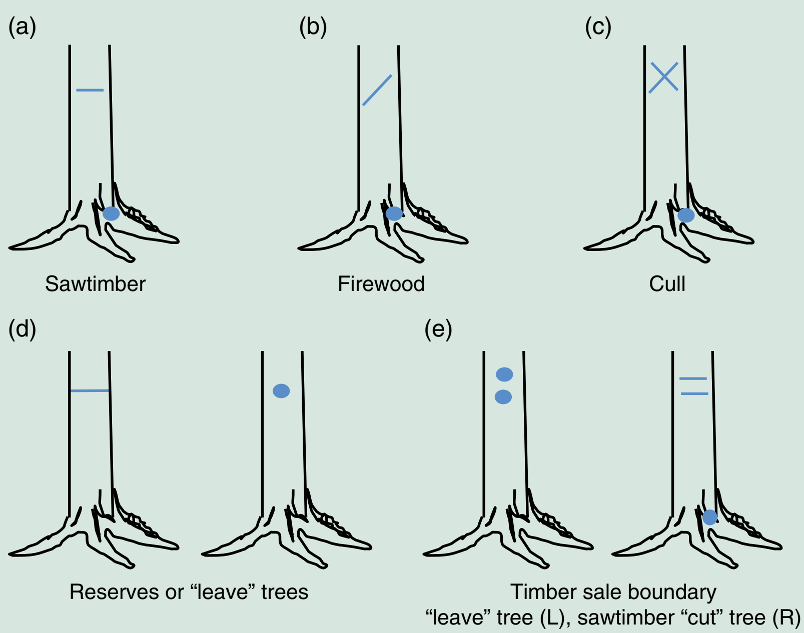
When preparing for a timber harvest or other activities on a plot of land, the first step should be to locate the boundary lines. Then, if some part of the area to be marked for cutting adjoins the property of another landowner, a strip of timber should be marked along that adjoining property line with double dots at eye-level (:) so that the cutting area is sealed off (see Box 23.1). The rest of the marking can then proceed without spending time worrying about wandering onto adjoining property. Much time might be wasted later checking into allegations that something has been marked on adjoining property. This is in contrast to the sale boundary, which is typically marked at the same time as the sale or soon afterwards. This line is in addition to the traditionally white blazes which determine the property line itself. While marking can be done right up to the line and even on some line trees, care should be taken that the evidences of the line will remain sufficiently obvious after logging, so that the lines can still be located. Boundary maintenance is sufficiently costly so it is better to leave trees that should otherwise be cut rather than to run the risk of losing the line location. Do not mark trees that are likely to be dropped onto adjoining property. If the line cannot be located, the "sealing-off strip" should be put far enough back from its probable location that so that there will not be any trespassing issues.

Public Roads

Strips along public roads and trails should generally be left uncut or lightly cut in such manner that logging debris will not be visible to people driving or walking by. Unless specific conditions necessitate it, these strips are often recommended to be about 50 ft (15 m) in width on

Box 23.1 Tree-marking guidelines for mixed native stands.

In marking timber, the most important consideration is to have a good reason for what is done. Marking procedures may vary by treatment or sale condition, but some general points apply to all treatments. Blue marking paint is generally the easiest to see (and less of a problem for those who are color-blind). Other marking colors include yellow, orange, and red. Where two treatments (stands) are adjacent to each other, different colors are preferable. Even if the the stands are all part of the same timber sale, it will help clarify which treatment is which. In most thinnings and selection regeneration methods, the trees to be marked are those to be removed. In uniform and irregular seed-tree, shelterwood, and coppice systems, the trees that are marked are usually those trees to be retained. See Fig. 1 for an example of timber marks used to denote different things. Tallied trees that are to be cut and that are merchantable should be marked with an additional stump spot. This helps the forester to keep track of which trees have been tallied, and which have not, during and after the felling operation. The stump spots are intended to remain after harvest, preferably placed in a crevice as low as possible with plenty of paint because the elements wear them off much more rapidly than what is above.



Box 23.1 Figure 1 Examples of timber marks used in the United States. *Source:* Mark S. Ashton.

either side. However, this can be reduced or otherwise modified if alignment of terrain or other visibility factors permit. Marking along roads should be done very carefully, usually as a separate operation, and it may help to have one person mark while another walks along the road to guide choices. Watch for telephone guy-wires extending out into the woods. While leaving a scenic strip will usually preclude any kind of cutting, nothing should be cut within the legal right-of-way of a public road or trail, and the edge trees should always be left.

Develop Methodical Timber-Marking Procedures (Logistical)

Trees or stands that are to be treated in a silvicultural prescription can be designated by (1) specification in words; (2) physical marking; or (3) some combination of both.

Treatments specified just by communication are usually done when it is either unnecessary or not feasible economically to make sophisticated decisions between trees. The simplest specifications are nothing more than designating that all trees over a certain diameter limit or all trees of a certain kind are to be cut. This approach gives poor or mediocre results. Better results can be achieved by laying out more definite rules or by marking small plots to demonstrate the type of cutting or treatment desired. The method works best by well-trained personnel who have no economic incentives to depart from instructions. This kind of approach is common in plantations with controlled spacing and single species, or in even-aged stands of single species. It is also more applicable for precommercial release and pruning treatments, where the economic incentive is not the harvest of timber itself but the production rate of treated trees.

Individual Tree Marking

A much closer degree of control, with less dependence on inspections, can be obtained by marking trees that are to be removed or those to be left. The loggers or workers are responsible only for removing the designated trees with care for the site and remaining vegetation. Marking individual trees for a silvicultural treatment is commonly done for mixed-species stands where understanding stand dynamics is critical or where the trees in the forest are very valuable. The forester therefore bears a much higher responsibility for planning both the logging and the condition of the future stand. Timber-marking procedures may vary with the planned treatment or sale conditions, but there are some general rules and procedures that will be helpful. Ordinarily the trees to be cut are the ones marked, because they are normally less numerous. This is particularly the case for thinnings. However, if the majority of trees are to be cut, such as in even-aged, or two- or three-aged regeneration treatments, then it is better to mark those that will be left. In cases where areas are to be cut completely clear, such as true clearcuts or one-cut shelterwoods, then it is sufficient to mark the boundaries of the stand to be treated.

Sometimes it is possible to combine verbal specifications with partial marking. For example, it may be useful to reserve and protect all trees below a certain diameter limit or size class, and those above that limit are specifically marked for removal. It might also be desirable to encircle specific patches of a stand for removal, and the remaining stand outside of the patches is limited to those trees marked for removal. The end-objective is to create a marking protocol that is efficient in time, minimizes costs, and ensures the best outcome from the prescription.

Guidance for Marking

Professional foresters who have attained responsible positions are usually too expensive for routine marking. Ironically, they do less and less of it but become more and more concerned about how it is done. They have become instructors and supervisors of marking instead of doing it themselves. They usually do little more than prescribe the marking method for the stand and then inspect the results. This is an argument for simplifying prescriptions, but in complex natural mixtures, it can mean the loss of one or more species, thus destroying the stand mixture. Having professional foresters in the field overseeing the actual prescriptions and marking of complex forest systems is an essential component of their sustainable management. Too often, foresters charged with managing complex native forests are to be found behind desks.

A forester who supervises timber marking must have personal proficiency and, above all, a clear idea of the ultimate objectives in the treatment of each kind of stand. These objectives must be developed in the light of a thorough understanding of local economic conditions, logging constraints, and the ecology of all species in the stand. If the marking of the timber is not done by the forester, then it must be conveyed to the staff, and this needs considerable effort in training and fieldwork.

Good judgement about timber marking can be developed through experience and observation in a given locality. The best test of the wisdom of a particular marking project comes a number of years afterward, when the vegetation has adjusted itself to the conditions created by the cutting. The pressures of forest administration are so great that it is too easy to concentrate on setting up this year's cutting, and to forget to go back to inspect the results of several years ago. It is also too easy to become obsessed with the virtues of an established marking policy, and to be blind to any shortcomings. The forester should take advantage of every opportunity to improve

skill in marking timber for cutting and then to observe results as dispassionately as possible.

Continuity and uniformity are needed in the treatment of individual stands, management of growing stock, management of stand structure, and pattern of logging. Prescription and marking rules are often the best way at describing and conveying the way trees are to be cut and treatments to be implemented. The use of tree classifications, sometimes with pictures (Fig. 23.1), depicting crown shapes, bark features, or other indicators of tree vigor can be helpful. It is helpful to specify the kind of stand to be left after the treatment. Such marking rules should not only describe the details of the marking itself but also indicate the objectives of stand treatments.

While rules can be useful, the insistence on conforming to them can inhibit the development of skill and good judgement among individuals. The extent to which this is true depends upon the knowledge and intelligence of the individual, nature of the rules, and the manner in which they are enforced. Rules by themselves are no substitute for the use of demonstration plots, training sessions, field exercises, and information exchange among personnel.

Mechanics of Marking

The first and foremost rule of timber marking as a forester is to communicate with those within a working group, or with associates for external consultation. Many times a thinning cut has become a patch-selection cut because two foresters envisioned a different structure of trees to be taken or reserved. It may be difficult, but the temptation to re-mark a fellow member's strip should be resisted. By communicating frequently in the woods, accidental re-marking can be avoided.

The marks themselves should be readily visible and durable enough in order to last through the period of the projected operation. This can be months to sometimes years, when the bureaucracy of a sale is slow, or the

(a) (b) (c) (d)

Figure 23.1 (a–d) Bark characteristics indicative of different rates of growth for southern red oak (from Burckle and Guttenburg, 1952), showing patterns typical of many species. As growth slows, the individual bark plates become larger and the fissures between them become deeper. A very fast-growing tree would have very smooth bark composed of small plates. *Source:* **(a–d)** US Forest Service.

markets are poor. Trees are normally marked with paint because of the ease and visibility it affords. The most common colors are blue and yellow. Red and orange can be used, but many people (mostly men) are color-blind to red and orange (Box 23.1). Marking was traditionally done with tools that scribed bark or with the use of axes, but this is rarely used now.

In order to mark a stand, it is best to work through the area in strips, which will usually be along the contour lines; this is to avoid walking up and down hills continuously. The paint marks should face the next strip so that you can look back and see what you have marked and where you have been. It will help the loggers if the marks are spread over as much of the stem circumference as reasonably possible. It helps everyone to know on which side of the tree to expect to see any marks.

All merchantable trees to be removed in a sale (sawlogs or fuelwood) should be marked at the stump, in order to confirm after the harvest that the loggers accurately followed the prescription they were given. Stump marks should be kept as low as possible, in order that the logger can utilize the entire stem without erasing the marking record. It is best to spray the paint in a protected spot such as a crevice, so it won't be rubbed off by logging machinery.

The shapes of marks may vary from one sale area to another to denote such things as fuelwood and sawlogs, or to identify trees of marginal merchantability which may or may not be cut at the loggers' discretion (see Box 23.1). Follow whatever scheme of shapes and colors of marks planned for the particular job and whatever scheme of tree measuring, tallying, grading, or species grouping has been set up for the particular sale. Keep checking any estimates you make, especially of the merchantable lengths of tree stems, a continually irritating source of potential error. Also be aware of trees which have abnormally large or small taper; such abnormalities have important effect on volume estimates. Trees that seem of acceptable diameter at the stump might have so much taper that their volume is actually very low. If in real doubt about this, err on the side of caution and mark it as fuelwood. The ultimate estimates of sale volumes are supposed to be as close to the truth as possible, but slight underestimates are better than overestimates of the kind that might leave the buyers feeling cheated. Finally, adherence to the standards of minimum merchantability is a serious problem.

Carefully Plan Haul Roads, Skid Trails, and Landings (Logistical)

Roads, skid trails, and hiking trails exist in almost every forest for recreation, access for monitoring and conserving rare and endangered species, access to protect and patrol the forest boundaries, and access for extracting timber and other products from the forest. All forests must have some form of access for people to carry out the management goals and objectives of the forest (Wiest, 1998). However, although access is essential, it is the road and trail system that is the source of nearly all water-quality problems (Reid and Dunne, 1984). Roads almost inevitably cause some degradation. The first step is to procure the appropriate equipment to be used on the roads and trail system. The second step is to determine how to avoid working on sensitive soil and wetland sites. Both would be considered under the umbrella of "conservation management practices" (Aust and Blinn, 2004).

Construction and Maintenance of Roads and Trails

Trails constructed for the foot-traffic of people and animals, and those left by the skidding of logs over the ground can cause problems. Roads can be worse because they are wider and cut more deeply into the terrain. The crucial consideration is planning how to remove surface water from rainfall as quickly as possible (Wiest, 1998). A forest road or trail should also be carefully planned to control the flow of water, but strong enough to support rolling vehicles or foot traffic (Fig. 23.2). Any action that removes or compacts mineral soil reduces its capacity to absorb and store water. The removal of unincorporated organic matter not only exposes soil particles to erosion, but also impairs the ability of these materials to arrest any particles that start to flow sideways (Reid and Dunne, 1984). Therefore, whenever mineral soil is exposed, it becomes important to prevent water from flowing for long distances over such surfaces and to divert it to the sides in some manner to be dispersed into the forest floor and litter.

The construction and maintenance of roads and trails are matters of engineering that are dealt with much more completely in review papers by Binkley and Brown (1993), Brown and Binkley (1994), Aust and Blinn (2004), and books by Stenzel, Walbridge and Pearse (1985), Satterlund and Adams (1992), and de la Cretaz and Barten (2007). There are also sophisticated GIS and spatial modeling programs that can provide guidance for road planning (Abdi *et al.*, 2009). Only the basic principles and some details about simpler kinds of roads and trails are considered here (see Box 23.2).

The basic solution to these problems involves measures that conflict with each other. The first is to quickly move the water off trails and roads. The second, which is much more difficult to achieve, is to prevent sediment-laden water from reaching streams. If at all possible, such water should be made to infiltrate into the soil before it reaches streams. The filtration can often be accomplished by diverting such water onto filter strips which are areas of porous undisturbed forest soil, but porous barriers such as bales of hay or artificial settling basins

Box 23.2 Harvest plan, skid trail design, and operations oversight of a ground-based timber harvest.

Design Considerations

- Locate roads and trails where water can be easily diverted. Avoid swales or low points and the high side of wet or steep areas. Trails should not follow watercourses or swales.
- The trails should be the minimum size needed for equipment.
- Skid trail grades should be less than 15%. Sections less than 300 ft (90 m) can be up to 25%.
- Prevent the accumulation of surface water on roads and trails through the appropriate use of insloping, outsloping, or crowned road surfaces, and culverts and waterbars. Waterbars should be at 30-35° from a line perpendicular to the trail and have an outsloping grade of 3%.

(a)

(b)

Box 23.2 Figure 1 **(a)** An example of a forwarder on rock and corduroy driving across an ephemeral stream. The coarse rock allows the water to continuously flow through during storm events. The rubber tracked surface promotes a smooth surface for driving loads of sawtimber across the rocks without disturbance. **(b)** A portable skidder bridge across a perennial stream with riprap bridge abutments for support. After harvest the bridge and abutments will be pulled out and used elsewhere. *Source:* **(a, b)** Mark S. Ashton.

Box 23.2 (Continued)

Box 23.2 Figure 2 An example of a skid trail that has been seeded back to grasses and forbs. *Source:* Mark S. Ashton.

- Use old landings whenever possible. When new landings are required, minimize the distance between the landing and public roads.
- Use appropriate drainage measures where necessary, to avoid the flow of water onto landings.
- Lay out harvest areas in a way that minimizes or eliminates skidder or forwarder activity in regulated areas of the harvest, which may include the designation of multiple landings where feasible.

Operational Considerations

- Use gravel or wood chips at the entrance to haul roads to prevent transfer of mud onto public roads.
- Skid across slope and uphill where possible.
- When wetland seeps have to be crossed, use corduroy or rock to avoid rutting (see Fig. 1).
- Control road access to prevent unauthorized use, which can compromise the integrity of roads and lead to increased soil transport. Permanent roads should have steel or cable gates. Seasonal roads should have cable gates or be blocked with boulders.
- Limit road use and skidding during periods of wet weather and prohibit during mud season.
- Require the proper disposal of hydraulic fluid, oil, and other operation-related wastes.
- Retire skid trails and landings when no longer in regular use. Remove all wood (limbs and blocks) from landings. Grade and drain roads as outlined above. On exposed soils, seed with appropriate grass and forb species and mulch as required (see Fig. 2).

are sometimes necessary. Many such measures are not permanently effective and must be repaired frequently until the eroding surfaces are stabilized. Where that is not possible, the objective should be to impose barriers in the streams that will slow the water down, so that the sediments will be deposited close to the source, and the cutting of streambeds will be reduced.

Erosion along roads, skid trails, and hiking trails, can be reduced by locating them so as to avoid steep grades and places where extensive cutting and filling will be necessary. It is desirable to avoid wet soils or very deep soils that are easily rutted when wet. On steep slopes, skid trails that converge downward should be avoided as much as possible. The location of roads and hiking trails close to and parallel with streams increases siltation and should be avoided. Proper attention to drainage of roads and trails not only reduces erosion but also prolongs their usefulness. This applies to roads and trails in continuous use, as well as roads that are only used periodically. If the drainage systems of temporarily abandoned roads cannot be cleared of debris periodically, they should be opened enough at the end of each period of use that they will function without attention.

It is frequently advantageous to suspend log transportation or vehicular traffic of any kind during periods when roads are muddy, because the risk of creating conditions favorable to erosion is then at a maximum (Yoho, 1980). Precautions of this kind often help reduce maintenance costs by preventing the damage and delay that occur when equipment gets stuck in the mud, and, more

(a) (b)

Figure 23.2 **(a)** A poorly graded and maintained road in Saskatchewan with no crown, slope turn-ups that divert the water into vegetated ditches and culverts. This should have been closed off, with water diverted by water bars, and then seeded. **(b)** A well-graded and properly drained all-weather logging road through a partially cut spruce–fir forest stand on poorly drained soil in eastern Maine.
Source: **(a, b)** Mark S. Ashton.

importantly, preventing the sedimentation problems that develop because of their use at a sensitive time of the year. In the case of access to cutting, some readily accessible stands on dry, well-drained soils should be reserved for muddy weather.

After the location of a road or trail has been determined, all trees and saplings in the way of the road should be cut before any earthmoving is done. Stumps must be removed and deposited in appropriate places; they often can be novel structures for wildlife use (e.g., dens, habitat cover) if positioned appropriately. Merchantable material should be converted to logs and put aside for removal when the road reaches the storage points. It is often very advantageous to form the bed and side-ditches of a road some months before the final surfacing material is applied and the road is put to use. This gives the roadbed time to settle, become firmer, and thus less subject to the rutting and other difficulties that aggravate erosion and damage to equipment. Even though it is porous, the topsoil must be removed or buried beneath the roadbed because it usually turns to mud if used as surface material for transportation (Wiest, 1998).

The next step is to apply any needed load-bearing surfacing materials, which are usually crushed rock or gravel. Ideally, the surface should be porous enough to absorb some water but also strong enough to support vehicles. Water-bars, dips, or culverts should be placed at strategic points along roads and trails to divert water into the forest. The spacing should be closer, the steeper the slope and the more erosive the materials (Box 23.2). It helps if roads have at least enough slope to prevent water from accumulating on them. Saturated surfaces usually lose their bearing capacity.

Paving prevents erosion of road surfaces but has the insidious effect of transferring the problem downstream. Fast-moving clear water, such as that which flows off paved surfaces (or even out of hard-bottomed streams) has tremendous erosive power because it will cut into streambeds until its total capacity to carry sediment is filled. Another kind of hard surface is that created by using bulldozers to create “hard-pan” roads. These are sunken ways more like ditches than roads. They are built by scraping down to some hard layer of subsoil. Because there is no place for diverting water to the sides, such roads usually become muddy, rutted sources of sediment during use. However, such roads can be acceptable if the hard surface is either natural rock or solidly frozen materials, provided that care is taken for disposition of the water that flows off them. Use of any sort of frozen roads should cease before thawing starts; their surfaces usually become supersaturated while they are frozen, so they become exceedingly muddy when they thaw.

Roads should be kept as narrow as possible in order to restrict the amount of exposed erosive surface. The temptation to use heavy earthmoving machinery to make roads wider than planned usually needs to be curbed. Measures that make roads more suitable for swift vehicular movement have the unfortunate effect of increasing the amount of soil disturbance. It may be desirable in engineering for bigger and better, but the ecology of the forest suffers.

Concerns about drainage of roads and trails change if the soil materials are highly porous sands. Erosion becomes a problem only during periods when the subsoil is frozen solid but the surface has thawed. Such soils lose their cohesion and bearing capacity if they are either too dry or supersaturated. At other times, they can often be used as roads without any ditches or excavation.

Proper bridges should be installed over most kinds of permanent streams, especially those capable of having fish. Culverts can be used for ephemeral streams, unless the waterway has large seasonal gulleys and then there should be a bridge. Fords can be used only where streambeds with permanently hard, rocky bottoms exist or can be created. For non-permanent skid trails, small intermittent streams can be crossed during the dry period by "corduroying" them, that is, by laying logs in the stream side-by-side and parallel to the streams, and the logs should be removed when the use has ceased. For non-permanent skid trails, permanent small or even ephemeral streams can be crossed using portable "skidder bridges" that are removed after use (Aust and Blinn, 2004).

The drainage of roads must be maintained and ruts and potholes should be filled. This is usually done with road-grading equipment that pulls material out of the side ditches and returns it to the middle of rounded road surfaces. However, the re-opening of some drainage ways can best be done with hand tools, preferably when water is actually running in them and blockages can be easily detected.

Many forest roads are used only for brief periods at intervals of some years. When such roads are taken out of use, measures must be taken to ensure that they will remain drained and uneroded without much attention. This is often done by digging "fail-safe" drainage ways that will carry water across and away from roads in deep ditches during heavy rains or similar events. High berms that are left beside ditches that cross roads will discourage damaging vehicular use of the roads. It is also important to see that exposed soil surfaces are promptly revegetated with grasses or other herbaceous vegetation, which may have some incidental value for wildlife. These measures not only reduce stream sedimentation but also help preserve the roadbed for future use.

Management of Road Networks

From the standpoint of protecting the watershed and conducting management activities, the objective of forest-road planning should be to make a whole forest accessible with the least possible amount of exposed road surface. This will also minimize the investment in roads in the long run. To this end, it is good to plan road networks that will serve all areas needing roads, and to extend them as necessary. Too often the networks grow in an unplanned fashion, as roads are built to whatever areas need harvests or access for whatever reason in the immediate future.

Because roads that are not in active use produce comparatively little sediment, there are advantages in some degree of concentration and consolidation of the harvesting activity, the recreational activity, or whatever activity that people demand within a watershed. To illustrate this point with an extreme case, if a fixed area of land is to be harvested in a given year, it would from this standpoint be best to concentrate it in one big clearcut area. This area might be served by one road that was open for use during that 1 year and then closed for a whole rotation. Such a plan would disturb much less road surface than the same area of cutting, if distributed around the forest in openings created by the group-selection system. The fact that large clearcut areas require less road-use than partial cuttings means that they actually contribute less of the main form of damage with respect to watershed management associated with timber harvesting. However, cutting reduces loss of water to transpiration, so that the concentration of too much heavy cutting in one watershed may sometimes induce excessive erosion of streambeds by allowing too much water to reach the streams (the 20% loss of forest cover rule; see Chapter 29, watershed treatment effects on yield). The planning of any system of forest roads should be done by attention to topography, soils, and geology. In steep terrain, it is very important to avoid putting roads on geologically unstable slopes subject to landslides.

The desirable widths of filter strips between roads and streams or lakes depend on the slope of the terrain. Recommendations by Simmons (1979) for the eastern US range are: 25 ft (8 m) for flat ground, 45 ft (14 m) for 10% slopes, 65 ft (20 m) for 20% slopes, 105 ft (32 m) for 40% slopes, and 165 ft (50 m) for 70% slopes, with doubling these widths for municipal watersheds. However, for most forests, and particularly forests managed for drinking water, stands with slopes that are greater than 40% should be designated as protection or reserve and should not be actively managed.

On very steep terrain, and on forests that are not municipal watersheds and that are managed primarily for timber, heavy cuttings may require networks of skid trails and haul roads that expose as much as 15–25% of

the soil surface. In most circumstances this is unacceptable and an alternative logging technique should be used (e.g., skyline or cable system, helicopter). An acceptable amount of land surface in trails and roads should not be more than 10%, with 5% being the most appropriate. The area that is permanently removed from production by haul roads varies significantly, depending on the kind of harvesting equipment used. It is very high if most of the movement of logs within the cutting area is done after logs are loaded onto trucks. The disturbance of the soil on skid trails is mostly temporary and so much less serious than that on haul roads for trucks, that it is desirable to accomplish as much movement of logs as possible in the skidding or harvest phase, rather than the transportation phase. However, in many parts of the the US and the world in general, small private forestland owners have few haul roads to maintain. The permanent haul road network is public road system maintained by the government.

Match Logging Machinery and Operation to Site and Economics (Logistical)

The kind of equipment used for moving logs to roads has an important effect on soil, water, and any vegetation being deliberately left to grow (Worrell and Hampson, 1997). There are two different means of log transportation: (1) those that lift the logs partly or completely off the ground and (2) those that drag (**skidding**) or carry (**forwarding**) logs on the ground (Stenzel, Walbridge, and Pearce, 1985). Those that lift do the least damage to the soil, but their effect on residual trees depends on how they are used (Box 23.3) (Greacen and Sands, 1980).

Cable-yarding with stationary engines involves lifting the logs into the air and moving them to a landing on a road. Dragging logs may cause some gouging and scraping action, but the heavy machines do not move over the soil and compact it. However, some modes of cable-yarding involve so much sideways shifting of the cables that almost all residual trees are knocked over; this kind of equipment is usually compatible only with clearcutting. On the other hand, with skyline systems in which cables are suspended above the stand canopy, it is sometimes even possible to lift logs out of the stands vertically in thinning operations. With this equipment, it is necessary to move the logs over well-defined corridors so that any partial cutting must be modified accordingly. Cable-yarding is generally adaptable only to steep terrain because substantial differences in elevation are required to place the cable high enough to lift the logs off of the ground.

One significant advantage of cable-yarding is that the machines do not burn fuel merely to pull themselves over the ground. In tractive skidding, the power source expends many times more energy in moving itself, than in pulling its load. This is one reason why logs are generally pulled downhill in tractive skidding, while it is both feasible and desirable with cable-yarding to pull them uphill. However, this also means that the road systems are often very different for the two general methods. With cable-yarding, the goal is to put the roads as high as possible on the terrain, but with tractive skidding they can be on lower ground. For these and other reasons, tractive skidding is usually cheaper than cable-yarding.

Helicopter-logging is very costly, but it reduces road building as well as damage to soil and the residual stand. With respect to these problems, balloon-logging is much like skyline-yarding except that the cableway is supported with a balloon rather than a tower. The use of these aerial systems in old-growth or mature timber leaves no permanent transportation system. This can be a blessing for watershed management and protection from trespass, but a curse for any other form of management that requires good access to stands.

Large mobile cranes with long booms and grapples are sometimes used to lift logs and then advance them by depositing them in piles that are two boom-lengths closer to the loading point. The crane is then moved (or "leap-frogged") to the other side of the pile to repeat the process which is sometimes called "shovel-yarding." This technique reduces the area of soil disturbance, but the swinging action of the boom requires that all sizable trees be removed from broad avenues through the stands. It is a common technique used on mountain slopes (e.g., Pacific Northwest).

Where heavy tractive machinery is used, the choice becomes skidding (dragging) or forwarding (carrying) out material with wheeled or tracked machinery as (1) logs bucked into short lengths, (2) whole delimbed stems, or (3) whole trees minus the roots. The longer the lengths that are pulled out of the woods, the greater is the risk of damage to the residual stand and the greater the need to arrange for movement along straight lines. When whole trees are dragged out of the woods, little gouging of the soil occurs, but there can be a sweeping of the litter, that may or may not be desirable, and destruction of advance reproduction. If the crowns are large, they may damage residual trees; such damage can be reduced by partial delimbing before the skidding starts. Carrying off the small branches and foliage can have serious consequences for the nutrient capital of the site. The practice of doing the delimbing at the log landings and leaving their vicinity choked with debris simply impairs the productivity of even more land. Sometimes this debris is carried back into the woods on return trips by grapple skidders.

Crawler tractors are less likely to cause rutting than rubber-tired devices because their weight is spread over

Box 23.3 Equipment considerations for timber harvest operations.

Box 23.3 Table 1 Harvesting technologies. A list of operational characteristics by soil, treatment size, and complexity.

FELLING (Fig. 1)	Operational characteristics
Hand felling	Suited to small-scale operations; over-sized trees (>16 in or 40 cm DBH) in regeneration harvests; steep inaccessible slopes or sensitive soils; individual large trees in selection systems
Small feller–bunchers (e.g., Morbell Feller Buncher)	Suited to small-diameter tree harvests; precommercial thinnings, pulpwood, or coppice systems. Equipment needs to work at scale on relatively flat terrain. Must be used with skidding operation
Small feller–processors (e.g., Makeri, Valmet Harvesters)	Suitable for maneuvering around and within plantations for pulpwood and small sawtimber thinnings. It pre-bunches cut-to-length timbers for forwarding operations. Tracked vehicles can reduce compaction on sensitive soils and can work on steeper slopes
Large feller–processors (e.g., Timco, Timber Pro, TimberJack)	Appropriate for large-scale operations with medium- to large-sized timber, either for regeneration cuts (seed tree, clearcut, shelterwood) or large-diameter thinnings for sawtimber. Logs are pre-bunched and cut to length for a forwarding operation. Given their tracked, 360° rotation, and ability to reach up to 15 ft (5 m), and to climb steep slopes, they are commonly used in forestry

MOVING	Operational characteristics
Forwarding operations	
Tractors	Farm tractors are ubiquitous with agriculture and match well with the farmer's woodlot or small private forest landowners. Appropriate for small-scale operations for firewood and small sawtimber
Forwarders (Fig. 2) (e.g., Valmet, TimberJack)	Specialized articulated vehicles that use well-designed skid-trails. They are more energy efficient for moving most weed, reduce compaction to the soil, and avoid scarification or destruction of advance regeneration. They are best on undulating or flat landscapes
Skidding operations (Fig. 2)	
Elephants, oxen, horses	Appropriate for small operations and areas that are steep or difficult to access. They create a small footprint per area harvested, but the trail area that is used is highly impacted. Only small- to medium-diameter logs can be moved
Skidders (cable, grapple)	Rubber-tired skidders can drag larger amounts and size classes for longer distances on terrain that can be steep and/or rocky as compared to forwarders. One end of the log is lifted off the ground while the other is dragged. The dragging can cause soil erosion and disturbance that destroys advance regeneration. The whole tree can be taken to the landing for processing, but the length can constrain the turns in the trail system, frequently causing damage to adjacent trees along the trail
Other kinds of operations	
Tracked crawlers	Bulldozers are widely used to drag large logs. Their tracks reduce compaction and increase traction on wet or clay-based soils. However because they drag, they destroy advance regeneration and, by rutting and scarification, can cause erosion. They are widely used in tropical rainforests to take out large logs but can be extremely damaging to soils
Yarding operations (Fig. 3)	Cable-yarders are appropriate for steep slopes. Operations can be small- to large-scale. Timber is cut to length and then dragged off the ground to the yarding deck that is usually roadside. If positioned sequentially along the road, cable-yarding can complete partial harvests (thinnings, selection, and irregular shelterwoods). Minimal impact is done to the soil surface
Skyline operations (Fig. 3)	Appropriate for large-scale timber harvests on slopes (mountains) that require the forest to be cleared for regenerations such as true clearcuts, seed-tree systems, or preparing for a new plantation. They are positioned at the top of ridges. Timbers are taken off the ground from the bottom of the slope to the top. Minimal damage is done to the soil surface since no vehicles or skid trails are necessary. Hand felling must be done. Partial cutting is difficult to accomplish
Helicopter operations (Fig. 3)	Only used for individual valuable timbers within remote forests. Also appropriate for salvage operations on steep slopes sensitive to erosion

Source: Mark S. Ashton.

(*Continued*)

Box 23.3 (Continued)

(a) (b) (c)

Box 23.3 Figure 1 Mechanized felling equipment. **(a)** A Makeri feller–buncher–processor, conducting a small-diameter geometric thinning that entails cutting, delimbing, and bucking to length, for a forwarder in a Scots pine plantation, UK. *Source:* Mark S. Ashton. **(b)** A Morbel feller–buncher that is cutting and pre-bunching pulpwood in a low thinning for a skidder in an aspen–birch stand in Maine. *Source:* Mark S. Ashton. **(c)** A Timco feller–processor conducting a crown thinning in a northern hardwood stand for large-diameter sawtimber in Vermont. *Source:* D. Hobson. Reproduced with permission from D. Hobson.

much more area. With any such machines, it is silviculturally desirable that they not be any heavier or larger than is necessary. It can help to use one device for assembling batches of material to be hauled out of the stand with another kind of device, especially when it is advantageous to collect small stems into bundles. Sometimes damage can be reduced if trees are cut into log lengths at the point of cutting, and left in piles to be brought out by

Box 23.3 (Continued)

(a)

(b)

Box 23.3 Figure 2 Skidding and forwarding operations. **(a)** Horse-logging a small 10-acre woodlot in Vermont. *Source:* Mark S. Ashton. **(b)** Using a rubber-tired cable skidder for small sawtimber and firewood harvest in Maine. *Source:* D. B. Kittredge, University of Massachusetts. Reproduced with permission from D. B. Kittredge.

(*Continued*)

large specialized trucks called "forwarders" that carry logs on their beds. Thus, there is no dragging and gouging effect associated with skidding.

Certain kinds of feller-bunchers, especially those with long arms that can reach out between the trees and bring in trees from several feet (meters) away, can reduce the amount of ground that needs to be run over in partial cutting operations. Some of these machines are designed to hold the tree stem while it is severed at the base, delimbed, and cut into logs left in piles for forwarders to pick them up. Sometimes the severed limbs can be left scattered on the ground in such ways that the machinery moves over them rather than on the soil. Some of these machines were actually designed for partial cuttings and

Box 23.3 (Continued)

(c)

(d)

Box 23.3 Figure 2 (Continued) **(c)** A bulldozer in a rainforest in Belize. *Source:* Mark S. Ashton. **(d)** A TimberJack forwarder. *Source:* Mark S. Ashton.

are not just construction machinery with special attachments for logging.

Skidding done with draft animals generally causes the least damage to residual trees and to the soil within the stand. However, because animals tire, skidding distances must be short, and this usually increases the amount of area in roads, which are the chief source of soil and water damage. The main problems with animals are that they are slow and require much care.

Many difficulties can be avoided if both timber markers and loggers plan for the felling and removal of trees. It usually helps to arrange for logs to be moved out in straight lines. If they have to be pulled around curves, it must be anticipated that any adjacent trees will be damaged; they can either be protected with buffers or simply harvested as a final step of the operation. Trees should not be felled parallel with skid roads or in such other orientations that the logs from them will have to be pivoted around good trees to move them to the roads. If trees are felled in a herringbone pattern in relation to the road, they can be pulled out with a minimum of turning. If they can be felled so that their tops point toward where they are to be moved, that reduces the total ground-skidding distance. However, it is often necessary to move the logs with the butt-end out first.

It takes cooperation and understanding between foresters and loggers to do good logging. The loggers must have adequate incentives. The cheapest possible logging is inevitably poor logging and ultimately invites public regulation. Almost any kind of equipment can produce good logging jobs if supervisors make it clear that good work is expected. It helps tremendously if all parties

Box 23.3 (Continued)

Box 23.3 Figure 3 **(a)** A yarder operation on a small mountain road in Austria. *Source:* Mark S. Ashton. **(b)** A skyline operation in the Cascade Mountains, Oregon. *Source:* Mark S. Ashton. **(c)** A helicopter-logging operation on Vancouver Island, British Columbia, Canada. *Source:* Mullins 2009. Reproduced with permission from R. Stanhope, Logging & Sawmilling Journal.

concerned would plan and think through what they do at each step, whether it be deciding which trees to cut, or how to move a skidder around in the woods to collect a load of logs.

Identify and Understand the Properties of Operable Soils (Physical)

Protecting soils from compaction, organic decomposition, and nutrient loss due to harvesting machinery and disturbance is the single most important aspect of maintaining site productivity (Greacen and Sands, 1980). Understanding soil types in relation to topographic relief, hydrology, and texture allows foresters to carefully plan silvicultural treatments by avoiding certain sensitive soils and excluding them from cutting treatments (steep slopes, rocky, sub-surface water), or by working at certain times of the year when soils are less sensitive to compaction and erosion (e.g., winter; dry season). Two major categories are described below: (1) sensitive topography, and (2) forest soil orders.

Sensitive Topography and Soils

Thin-soiled ridgetops and other ledgy areas: these sites are so poor and so exposed to wind damage and drought that it would be unwise to lavish much attention on them. They are also difficult to access and hard to operate any kind of machinery. They would be best allocated to a reserve system within managed forests.

Steep slopes prone to landslides: while the cutting itself is not likely to start surface erosion, it may induce landslides or other deep-seated earth movements on extraordinarily steep, geologically unstable slopes. Most of these kinds of sites in North America are found in small portions of the very steep and geologically young coast ranges along the Pacific Ocean (Swanston, 1974). However, similar conditions can exist on other steep terrain. The causative conditions are not steepness alone, but the existence of discontinuities of soil materials a few feet (meters) below the soil surface that can become planes of slippage, especially when lubricated by water. If the roots of large trees extend downward across these slippage planes, the risk of landslides is reduced. The action of webs of tree roots can bind the surfaces together well enough to reduce the tendency for lenses and slabs of material to slide or slip down the slopes. If too many trees are killed by cutting, the web of tree roots is likely to decay after several years and cause delayed-action landslides and mudslides. Whereas any surface erosion is most serious immediately after soil disturbance, this kind has the insidious characteristic of occurring years later.

As in the case with surface erosion, these destructive events are much more likely to be caused by roads and road-building than by the cutting pattern. If landslides are likely to occur on a particular steep slope, there will usually be leaning trees, soil creep with trees showing evidence of bending upward from trunks that have tipped, or some other evidence of surface soil movement having taken place. However, knowledge of the subsurface geological structures is often necessary to detect dangerous situations. Susceptible areas are best logged with helicopters or balloons, without roads, or not logged at all. For most of these slopes it is not a question, from the geological standpoint, of whether there will be landslides, but only of when and at what rate. If such areas are going to be subjected to cutting at all, it is logical to employ kinds of selection or irregular shelterwood cutting that will encourage the permanent maintenance of a network of living roots. Applying harvest treatments to slopes would require knowledge of its steepness, proneness to earth-slip, and downslope impacts such as homes and other properties.

The Properties of Forest Soil Orders and their Sensitivity to Harvesting

Glacial soils (inceptisols, spodosols): most glacial soils are **inceptisols** restricted to the northeast and north central US, almost all of Canada, and the higher elevations of the mountains in the western US. Not all ridgetops are dry and thin-soiled. Drumlins composed of till soil up to 150 feet (50 m) thick, many of which are still in agricultural use (or recently abandoned), can be very productive, but have sensitive subsurface waterflows during spring snowmelts or wet periods of the year and logging during this period should be avoided. Dry glacial tills and outwash are perhaps some of the most resilient soils to work with. The rocks in till soils tend to reduce proneness to compaction, and the sandy, coarse-textured soils of outwash and moraines tend to be well drained and tolerant of heavy machinery.

Spodosols are mostly soils of cool to cold wet climates, usually associated with conifers of the eastern boreal of US, across boreal Canada, and high elevations of the US northwest. They are nutrient poor, occurring within well-textured, nutrient-poor geology (sandstone, granite). They have large organic accumulations and bleached sandy soil mineral horizons immediately below the organic layers, derived from the humic acid leachates from above. Roughing up the organic layer and exposing the mineral soil can sometimes be beneficial for seedling germination, but care must be taken not to promote erosion.

Non-glacial upland soils of the east coast (ultisols): in the eastern US where glacial soils end, **ultisols** take over. They are the dominant soil on the old weathered uplands of the southeast and mid-Atlantic states. There are no rocks because of their ancient weathering, and the red–orange color is from iron oxide. These soils typify forests of wet temperate and tropical climates. Nutrients held in these soils are easily lost through erosion from soil

exposure, mostly from agriculture (i.e., the Piedmont). Rich in kaolinite clays, care must be used to protect the surface horizons from loss of organic matter. Many are deficient in calcium and potassium. Ultisols with thicker organic horizons can be found on the western lower slopes (non-glaciated) of the the mountains in the Pacific Northwest. The higher proportion of sand in the upper soil horizon makes them very erosion prone. Careful harvesting needs to be done year-round given their proneness to compaction because of their clay content and sensitivity to erosion, and because of their association with sloped topography that can be steeply dissected. Waterways need careful protection and wider forest buffers to protect from sediment erosion, compared to those on glacial soils that are thin and rocky (Yoho, 1980).

Non-glacial upland forest soils of middle America (alfisols): bisecting the country from Wisconsin south to Texas, **alfisols** dominate the seasonally dry uplands – the oak woodland and pineland forests of the uplands bisecting the Mississippi River valley. These soils are less weathered than ultisols, more nutrient rich, and therefore have mainly been converted to agricultural uses. They are rich in clay and iron, and therefore are red in color, and high in cation-exchange capacity and nutrients. They are less prone to erosion and most have a structure that makes them more resilient year-round from impacts of harvesting machinery compared to other soils.

Western soils (andisols, aridosols, spodosols): soils of the Intermountain and southwest regions of the US are dominated at low elevations by **aridosols** (desert soils). These soils are high in salts at the soil surface and through irrigation can be productive but very prone to salinization. They can be dominated by pinyon–juniper but more often by open desert plants or sage brush. Some have been converted to intensive irrigated agriculture and a few to irrigated tree plantations. Many have succumbed to salinization and are now toxic to plants because of surface salt concentrations.

Andisols are all found beneath the conifer forests of the Pacific Northwest, associated with volcanic deposition. They can be very fertile and productive soils, but are prone to mudslides and landslides on mountain slopes (see the section earlier on steep slopes) primarily because of slippage from the discontinuities of volcanic deposits of different epochs.

Alluvial (entisols): **entisols** are all young, continuously deposited, or moving soils, whose mode of deposition is wind or water. The alluvial soils of river flood-plains and the sand plains and deltas of coasts are the most relevant entisols for forestry. These soils can occur embedded within the other soil orders of the region because of the movement and actions of water. The clay-based flood-plain soils are some of the most sensitive but most fertile soils for forests, and are very prone to compaction at all times of the year. Care must be taken to use special machinery. Sandy coastal soils can be nutrient poor but less sensitive to compaction. Care must be taken to retain all nutrients and organic matter to maintain water-holding capacity and fertility.

Protect Wetlands, Permanent Streams, and Bodies of Water (Physical)

The protection of temperature and quality of water necessitate dealing with wetland areas and water courses in the same general manner as strips along public roads (Gregory *et al.,* 1991). One objective is to prevent the felling of trees into the water and skidding across any kind of perennial or ephemeral stream; another is to ensure that shaded cold water remains shaded. The screen of trees along lakes and ponds should not be interrupted so as to prevent gaps in the wind-screen. Ultimately, narrow belts of uneven-aged stands could be developed in those places or they could be incorporated into the reserve system of the forest.

The term "wetlands" includes any of the soil types designated as poorly drained, very poorly drained, alluvial, and flood-plain (including submerged land) by the National Cooperative Soils Survey of the Natural Resources Conservation Service of the United States Department of Agriculture. Different states use various modes of identifying wetlands, using plant indicators or the nature of soil mottling and gleying.

The term "watercourses" includes rivers, streams, brooks, waterways, lakes, ponds, marshes, swamps, bogs, and all other bodies of water, natural or artificial, vernal or intermittent, public or private. "Intermittent watercourses" are delineated by a defined permanent channel and bank, and the occurrence of two or more of the following characteristics: (a) evidence of scour or deposits of recent alluvium or detritus, (b) the presence of standing or flowing water for a duration longer than a particular storm incident, and (c) the presence of hydrophytic vegetation.

Most states require, by law, streamside management areas or zones (SMA or SMZ) around all watercourses, as defined above. The width of these buffers needs to be sufficient to prevent any delivery of sediment and nutrients to the watercourse from logging, and needs to prevent any increase in water temperature from reduced shading (Fig. 23.3). SMZ width depends on the slope, soil type, the amount of precipitation, and its seasonality of melt and flow in water bodies (Box 23.4). State width regulations obviously vary, with states like Washington having very large buffers (>300 ft or 100 m) because of the tall canopy heights of the trees, the steep slopes, and the very erodible stream morphologies (Keim and Schoenholtz, 1999). In the eastern US, buffers can be as low as 25 ft (8 m) where slopes are less than 15%, streams

Figure 23.3 Streamside management zone (SMZ) within a young loblolly pine plantation in East Texas. *Source:* Simpson, 2002. Reproduced with permission from Texas A&M Forest Service.

Box 23.4 Design of streamside management zones (SMZs) or water quality zones (WQZs). Water quality zones are defined as the area occupied by wetlands and watercourses. Examples of WQZs are perennial and ephemeral wetlands, ponds, seepages, and streams.

Water Bodies

Design

- Retain appropriately sized buffers of trees and protect the forest floor around all perennial ponds, wetlands, streams, and vernal pool depressions. The minimum width should be 25 ft (7.6 m). Buffer width should be increased on steeper grades: approximately 20 ft (6 m) for every 10% change in grade.
- Thinning of buffers may be appropriate to increase edge stability, age-class distribution, and structural diversity.
- Delineate and mark all WQZ buffers in the field during initial reconnaissance of the harvest area. Use blue flagging to mark zone boundaries. For WQZs defined as perennial ponds, wetlands, streams, and vernal pool depressions, boundary trees should be painted with double dots to clearly indicate that such areas are excluded from harvest operations.
- Identify all major WQZs on harvest area maps and point out their location to operators in the field.
- Maintain a minimum distance of 150 ft (46 m) between WQZs and any road or skid trail.
- In regeneration treatments retain a minimum of 50% canopy coverage of regularly spaced crowns within 50 ft (15 m) of any WQZ. Be sure to maintain sufficient shade within 50 ft of any vernal pool. Exceptions may be made in some cases for the express purpose of promoting aquatic habitat diversity through increased radiation and temperatures.

Operational

- Schedule any machine activity in timber sales with sensitive WQZs during extended dry periods or when the ground is frozen or covered in snow.
- Keep all tree tops and slash at least 50 ft (15 m) away from all WQZs. Leave natural debris in WQZs undisturbed.

Watercourse Crossings

Design

- Minimize the number of watercourse crossings.
- Make any crossings perpendicular to the watercourse and ensure sufficient flow.
- Use appropriate erosion- and sediment-control measures on all temporary crossings, e.g., riprap, skidder bridges, or culverts.
- Require all watercourse crossings to be designed or approved by licensed foresters working with operators.
- Whenever possible, use watercourse crossings only during dry times or when soil is frozen.

Operational

- Prohibit skidding or driving through flowing streams.

slow moving, and canopy stature is low, but generally stream buffers are about 50 ft (17 m). All buffer widths should have more than a single row of trees so as to withstand wind damage. Many SMZs are reserves where there is no cutting, and large trees are left purposely to provide for bank stability. Large woody debris is encouraged to occupy the stream-bed itself, to guide and regulate water flow and provide fish habitat (Murphy and Koski, 1989). In some instances, thinning and selection regeneration methods can be used to encourage bank stability, high groundstory vegetative stocking, and greater vertical foliar diversity, making for a much more resilient buffer area (see Chapter 29 for more details).

The most common case where clearcutting alone can cause true site degradation is on soils that are continually wet and poorly aerated, particularly those with *Sphagnum* moss. This is not something done currently, but it is something that has happened and now concerns restoration and reforestation. These are usually on the flattest kinds of terrain, but they can also be on hillsides where precipitation grossly exceeds evapo-transpiration. Mossy hillside moors are common in many areas of Britain and Ireland, where forests were cleared and repeatedly burned for grazing, hundreds or thousands of years ago. Problems of excess water were aggravated by the development of podzol hardpans induced by strong leaching. Reforestation often depends on deep plowing, done to break the hardpans and allow water to drain from the surface soil layers.

In many forested swamps and bogs, transpiration by trees plays a major role in keeping water tables low enough for the roots of the trees to survive. If clearcutting turns off the "transpiration pump," the level of poorly aerated water may rise enough to retard or even prevent re-growth of trees. This is one of the few cases in which complete clearcutting by itself can actually defeat the growth of trees. Partial cutting is the best solution to these problems.

In current forestry, wetland soils are usually regarded as no-cut zones or part of a permanent reserve system. Avoiding wetlands and sensitive soils such as seeps and vernal pools needs to be planned at all kinds of scales that depend upon the nature of the climate, soils, topographic landform, and underlying geology.

Avoid Close Utilization on Certain Sites to Protect Site Productivity (Biological)

The most important risk of nutrient loss comes from removing the nutrients in wood, leaves, or litter. Some of the practices associated with agriculture on marginal land in less-developed countries (and formerly in Europe) are very deleterious. Repeated removal of litter from forests for mulch or fuel is perhaps the best way to ruin the soil (Pritchett, 1979); it often leads to the development of very slow-growing forests. Excessively close utilization of foliage or twigs for fodder, fuel, or simple wooden structures also places a nutrient drain on forests (Moench, 1989; Wenhua, 2004). Regardless of what defects it may have, it is better for people to use the coppice method to grow fuelwood than to ruin the soil by scraping up litter and animal dung to use for cooking their food.

The concentration of chemical nutrients in leaves and twigs of trees is much higher than in the mainstem wood and bark, but roughly half of the total weight of nutrients is in the mainstem. Sometimes the heartwood of trees has lower concentrations of nutrients than the sapwood, and the proportion of heartwood increases as trees grow older (Raison and Crane, 1986). If removals are limited to pieces of wood about 4 in (10 cm) or larger in diameter, the nutrient losses are usually offset by supplies of nutrients from (1) rock weathering (2) nitrogen fixation, and (3) aerial forms such as desert dust, evaporated ocean spray, nitrogen fixed by lightning, and the substances of atmospheric pollution.

The same problems associated with removing twigs for fuel by labor-intensive means could also arise where highly mechanized harvesting can chip whole trees for pulp or fuel under circumstances in which the labor needed for manual delimbing is too costly. The losses can be reduced considerably by growing trees to larger size and lengthening intervals between the removals (Raison and Crane, 1986). They can also be reduced by measures such as harvesting trees when they are leafless or by delimbing at the stump and thus leaving the twigs, leaves, and branches on the site. If the depletion becomes too great, it may be necessary to apply fertilizer, just as is the case in the essentially depletive practice of agriculture. It is more effective and cheaper to maintain optimum amounts of organic matter, especially that incorporated in the soil, than to resort to fertilization (Stanford and Smith, 1972). Fertilization is better viewed as a means of improving the productivity of undamaged soils than as a remedy for improving degraded ones.

Maintain Structural and Biological Diversity (Biological)

Much of what is described below is more explicitly discussed in Chapters 26 (forest health) and 24 (wildlife), where silvicultural treatments for these values are the primary objective in forest management. However, even in the most intensive tree-cropping systems, many of the practices suggested here to maintain wildlife and biological diversity can be implemented within silvicultural treatments, even if they are secondary goals. In almost all forests of planted or natural regeneration origin, biodiversity and wildlife are now important factors to include (see example in Box 23.5). Obviously it is much easier to work these considerations into native forests that already

Box 23.5 Considerations to promote structural and biological diversity of a southern New England forest to maintain productive capacity and healthy functioning.

Stand-Level Practices

- Prohibit high-grading or other actions motivated purely by short-term economic gain.
- Wherever possible, retain snags and current or potential den trees in a range of sizes, except where unsafe. Keep all snags bordering large openings (i.e., clearcuts and seed-tree cuts) or wildlife openings. Aim to keep approximately five snags per acre, one den tree per acre (12 snags per hectare, 1 den tree per half hectare), and all den trees within 100 ft (30 m) of wetland and riparian zones.
- Where stands are vulnerable to invasive species, design silvicultural prescriptions (e.g., release treatments such as shelterwoods) that minimize the potential for these species to spread by facilitating and ensuring growing-space occupation with advance regeneration of desirable species prior to release.
- In regeneration cuts maintain, where applicable, a variety of soft and hard mast tree reserves to provide food for wildlife.
- Protect all cultural wolf-trees as older elements of the forest and sources of structural diversity.
- In regeneration treatments, maintain seed trees of species that will add diversity to future stand compositions.
- In certain regeneration prescriptions take advantage of the topography, soils, and adjacent water bodies to leave single or groups of reserves (often hemlock) for structure and thermal cover.
- Where appropriate, expose rocks, slash piles, or stone walls to increase surface temperatures, particularly in thinning treatments. Increase ground cover heterogeneity.
- Consider leaving several slash piles of 4–5 ft in height and diameter per acre (1–1.5 m in height and diameter) for wildlife or using high slash for seedling protection.
- Keep several logs per acre that are greater than 12 in (30 cm) DBH and at least 6 ft (2 m) in length.
- Employ loggers with a good reputation and a demonstrated ability to minimize residual stand damage.
- Encourage in-woods processing (e.g., cut to length near stump) whenever possible to reduce residual stand damage.
- Minimize the amount of logging in springtime, when bark is easily damaged.
- Require the use of felling and extraction techniques that protect advanced regeneration or (where regeneration is insufficient) create conditions that promote regeneration within 3 years.
- Use bumper trees on trails to minimize residual stand damage.

Landscape-Level Practices

- Promote or maintain a diversity of forest cover types (i.e., stand composition). Where appropriate, consider maintaining some small openings for wildlife (e.g., meadows, early successional patches).
- Promote or maintain stands of various ages and different stages of stand development across both single- and multiple-age stands.
- Stands of different types and ages should be distributed across the landscape in an irregular, patchwork arrangement.
- Minimize fragmentation by treating whole stands.

have a good deal of inherent structure to work with and maintain the single-aged, single-species plantations. The two spatial scales to consider are at the scale of the stand at which silvicultural treatments are implemented, and at the scale of the landscape or watershed at which planning, arrangement, and temporal implementation of treatments across stands gets implemented. Promoting both structural and biological diversity in managed forests can provide many long-term benefits, including promoting the resilience of forests to damaging agencies of insects and disease, reducing risks from climate changes over seasons, years, and decades, and lowering risks from soil degradation and loss of productivity. They are often factors that are hidden and difficult to quantify in terms of economic benefits, but many studies are beginning to demonstrate the economic costs of not considering and promoting these factors within managed forests (Pimentel *et al.*, 1992, 1997; Grime, 1998; Lindemayer, Margules and Botkin, 2000; Hartley, 2002; Carnus *et al.*, 2006).

At the scale of the **stand**, there is a variety of forest structures and biodiversity considerations to incorporate within a silvicultural prescription. There are 10 of these.

- The first can be considered the nature and distribution of wood that is left behind. Standing dead snags or trees that will become standing and dead snags are critical structures that need to be included in a prescription. Different forests have different baseline size class and densities of snags that can be used as guides (Farris, Huss, and Zack, 2004; Hunter and Schmiegelow, 2011). This is particularly relevant for even-aged and two- to three-aged systems that are primarily driven by one cohort which goes through a relatively homogeneous period of early successional growth where snags are often missing. Standing dead trees are critical habitat elements for birds and arboreal mammals that eat larvae feeding on dead wood (woodpeckers, nuthatches) (Cline, Berg, and Wight, 1980; Newton, 1994).

- Similarly, leaving substantial amounts of larger-sized woody debris along with the remaining slash after the harvest is an important factor for maintaining a diversity of both microfauna and flora (fungi), which are important for the decomposition processes of the forest soil, and that in themselves serve as a food source for invertebrates (particularly annelids and arthropods), and that in turn serve as a food for amphibians, birds, and small mammals (Harmon *et al.*, 1986; Harmon and Hua, 1991; Sturtevant *et al.*, 1997). The wood thus serves as a base substrate for maintaining a much more complex trophic foodweb (Powers, Tiarks, and Boyle, 1998; Hagan and Grove, 1999).
- Another structural attribute that promotes biodiversity is both identifying and protecting older legacy trees within younger stands, and planning for their successors. These should be species representative of the late-successional forest that already have characteristics of maturity, large-crowned, emergent, and expansive. Many have the added value of producing an important food source for a variety of animals through their fruits (cherry, persimon) and nuts (oak, hickory, pine). Given their maturity, many show signs of decay and cavities that become important den trees for mammals, and nesting sites for cavity-nesting birds (Hunter and Schmiegelow, 2011).
- Treatments should always strive to create vertical complexity as much as possible in open, early-successional regeneration treatments and in homogeneous single-canopied forests, such as single-aged, single-species plantations. Of course, this runs completely counter to maximizing the homogeneity of the treatment to ensure uniformity of stand growth. A compromise must be developed. Vertical canopy structure is a highly desirable element in diversifying habitats, particularly for birds and insects. Shade-tolerant evergreens (e.g., hemlock) as an older tree grouped beneath other deciduous legacy trees greatly increases the structural value of the arrangement because of its year-round thermal properties and high live-crown ratio (Hunter and Schmiegelow, 2011).
- Ensure that the occupation of the open growing space in a regeneration method is complete, with the intended tree regeneration in as short a period of time as possible. In forest types dependent upon advance regeneration, it is important to establish full occupancy before canopy removal, as much as possible. The sprout growth of understory species, when not impeding other forms of tree regeneration, can be a very important filler. All of this is to deny the ability of invasives to overtake the growing space before the forest is fully established. Most plant invasives are opportunists and site generalists but require full sun for best establishment. Ensuring full stocking of regeneration and moderating canopy shade will preclude invasive plant colonization (Wittenberg and Cock, 2001).
- Always follow the protocol of ensuring that logging machinery has been washed before arrival to prevent contamination by invasive plant seed, pathogens, or insects (Wittenberg and Cock, 2001).
- For forests that are dependent upon advance regeneration, careful planning of extraction trails and the machinery used to harvest the trees needs to account for protecting as much of the advance growth as possible.
- Harvest when forests are dormant (dry season, fall, winter). Spring and early summer is a very important period for nesting/breeding birds, mammals, and amphibians (Hunter and Schmiegelow, 2011). In addition, spring time is a period when a tree is actively growing and is much more susceptible to logging injury because the bark is so easily dislodged from the active cambium.
- Set aside any novel microhabitats in species composition and structure within the stand as group- or patch-reserves (Noss, 1991).
- Ensure that the adjacent stands promote linkage and connectivity, and moderate the landscape impact of the treated stand on wildlife movement and habitat change. This is difficult to assess, but usually all waterways can serve as protected reserves of mature forest that all serve as connective elements between managed stands, including different age classes (Noss, 1991; Bennett, 1998).

Landscape-level factors to consider involve the spatial and temporal planning and arrangement of stands within sub-watersheds and watersheds that in themselves are defined by underlying geology and scale of topographic relief. Baseline guidelines in the scale and arrangement of stands within watersheds have been discussed in Chapter 3 (site classification, stands as management units, and landscape planning). Conservation management practices can include the following:

- allocate a portion of the landscape to reserves that includes stands of late-successional trees; The proportion allocated could be based on the “triad approach” (see Chapter 3 for details) (Noss, 1991);
- reserves should represent the habitat and community types found within a managed watershed (Hunter and Schmiegelow, 2011);
- representative age classes should be carefully juxtaposed adjacent to each other, within a watershed (Hunter and Schmiegelow, 2011).

Preserve Cultural Legacies of Land Use (Cultural)

Cultural impacts on forests are now pervasive, and important legacies in many states, provinces, and nations have designated these structures to be protected by law. In the northeastern US, stone walls, cellar holes, and “wolf trees” (old, large trees that grew in the open pastures of a once pastoral landscape) can all be considered an important part of a landscape cultural heritage and should be protected. Native American footpaths, fishing

dams, camp sites, and ancient swiddens are all important to protect within CMPs. In places like Hawaii, evidence of ancient terraced agricultural systems should be included. In many tropical forests, individual trees within rainforests have been planted and tended for fruit, food, or medicine, and are the property of individuals even though the forest is owned by the government or community.

In the western US, where the imprint of indigenous peoples has been more evident, culturally modified trees (CMTs) are old trees that have had their bark stripped or portions of their wood taken for foods, implements, canoes, totem poles, and house construction. Many of these trees are western redcedar, Port-Orford cedar, and Sitka spruce, but western hemlock, ponderosa pine, and lodgepole pine are also common.

In many regions (south Asia, central Europe, Near East, west Africa, northeast Asia), complete forest areas can be regarded as sacred with no cutting. They are called sacred groves or temple forests and often surround temples, churches, shrines, and burial grounds. In those same regions, many trees are regarded as sacred and cannot be cut wherever they may be. The most important and significant tree is the Bo tree (*Ficus religiosa*) under which the Lord Buddha attained enlightenment while meditating (Table 23.1).

Table 23.1 Descriptions of a few important trees of cultural and sacred value that should be protected. There are many species and individuals that should actually be recognized but these are some examples.

Trees of Asia	
Cryptomeria japonica Sugi	A tree from which the central pillar of traditional houses is used to bless the house and keep it safe
Ficus religiosa The Bodhi tree	The fig tree under which the Buddha attained enlightenment
Hopea odorata	The veneration of the tree brings luck. The wood is used in parts of boats and houses to bring luck and safety
Tamarindus indica The tamarind tree	Associated with Hindu deities
Trees of Africa	
Bombax buonopozense *Cordia melleni*	In West Africa, certain trees serve as meeting places and are associated with sacred groves
Ceiba pentandra	In Senegal this tree is linked to curing mental and psychological problems. In general, it is seen as a sacred tree throughout the region
Chlorophpora excelsa	A tree with general sacred properties throughout the region
Copaaifera religiosa *Guibourtia tessmannii*	Both trees are signs of wealth and fecundity in Cameroon
Trees of Europe	
Betula pendula Birch tree	Often sacred to Scandinavian peoples
Crataegus spp. The Glastonbury thorn	The hawthorn is regarded as sacred to many Christians
Quercus spp., and *Fraxinus* (oak and ash)	Especially important trees to Celtic countries in fairy lore with hawthorn
Taxus spp. Yew	Commonly associated with immortality – planted in graveyards
Tilia spp. Lime tree (basswood)	A tree of hospitality in France planted in front of houses; a tree of justice planted in the center of villages in Germany
Ulmus minor Elm	The tree symbolizes death and transition to the underworld and is planted in cemeteries in the UK and France
Trees of North America	
Thuja plicata Western redcedar	Virtually every part of the tree has a cultural use to Native American peoples of the west coast, including houses, totem poles, and masks
Quercus spp. Oak	Individual oak trees were often revered by Native Americans for healing and sustenance (e.g., the Chinkapin Oak of the Lenape Indians in Pennsylvania). Many individual oaks are revered in history (e.g., the Charter oak of Connecticut)
Picea sitchenensis The golden spruce	A religious tree of the Haida, Queen Charlotte Islands, Canada
Sequoia gigantea Giant sequoia	The world's largest trees are revered because of their size

Source: Mark S. Ashton.

Aesthetics and Landscape Planning

The last component of a set of conservation management practices to consider is the aesthetic aspects of a forest, and the potential mitigation involved in silvicultural treatments that adversely affect open-space recreation. Chapter 28 covers the incorporation of aesthetic design into forest planning in greater detail than here. The major considerations relate to integrating landscape-design principles into forestry practices to preserve and sometimes enhance the scenic quality of managed forests.

Some important operational principles are:

- stumps should be cut as low as possible to reduce visual impact;
- cut all bent-over or severely damaged trees in large openings and lay the stem flat on the ground (unless it is a snag or den tree);
- leave landings free of blocks, unmerchantable stems, and other slash;
- keep all slash at least 25 ft (7 m) from public roads or property boundaries;
- keep all slash within 100 ft (30 m) of public roads and trails less than 2 ft (0.6 m) in height; all tops and other slash in the remaining area of the stand should be less than 6 ft (2 m) in height.

Some important stand-level principles are:

- retain individual trees of aesthetic quality wherever possible (e.g., wolf trees); these trees are often of value for wildlife and culture at the same time;
- "feather" the boundaries of treatments by keeping trees at various densities and sizes near the edges of openings;
- use visual buffers along public roads and trails and on exposed ridgelines which should be at least 50 ft (17 m) wide, but the length should depend upon the scale of the treatment and the density and stature of the vegetation;
- even-aged regeneration methods (true clearcut, seed-tree, and shelterwood) are best softened by making them irregular (two- to three-aged irregular systems) with group and single-tree reserves and stand boundaries that should be irregular in shape.

A landscape-level principle is:

- harvest adjacent stands at different times, at least between 5–10 years apart, depending upon the variable growth rates of the forest trees.

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24

Silviculture for Wildlife Habitat

Introduction

Forested ecosystems are the natural cover of only one-third of the earth's land surface, but they contain a large fraction of the plant, animal, fungal, and microbial species of the world. Because forested areas have been reduced in many regions by agricultural and urban development, it is important that management of forests for timber, watershed protection, and other purposes includes measures to maintain native species. Furthermore, public policy increasingly stipulates that this be done. Treatments of forest vegetation can also be designed specifically to improve habitats for species of particular concern.

The earliest silvicultural treatments were designed to maintain supplies of timber and fuelwood, but management of forests for wildlife populations has also had a lengthy history. Prescribed fire, tree cutting, and planting of preferred food species were used both by aboriginal peoples to improve subsistence hunting and by medieval gamekeepers to improve sport hunting and meat production for the upper classes of society. However, predator control and regulation of hunting were the main management tools used until fairly recently. A scientific approach to habitat management was developed in the 1930s, as the concepts of ecology were applied to traditional methods used for managing game species such as deer and grouse (Leopold, 1933). This ecological view tended to give more attention to the associated plant and animal species that formed habitats and food chains that supported game species. Recent management ideas have more explicitly included all organisms existing within an ecosystem; thus, the terms and concepts of wildlife management are increasingly becoming associated with all of the native flora and fauna of a region (Hunter, 1999, 2010). However, concern for animals still tends to predominate in most wildlife-management efforts.

Forest habitat management has several general kinds of objectives. In some cases, the emphasis is on a single species, and much of this kind of **species-oriented management** continues to focus on game species for sport hunting, but an increasing focus has been for the recreational viewing and photographing of animals. These two objectives often involve the same large mammal and bird species, but "watchable wildlife" includes a wider range of species than is considered for hunting. Other species become the objects of intensive habitat management because they are locally rare or are in danger of extinction; these may include organisms in any taxonomic group. A quite different objective of management is the **conservation of regional biodiversity**. This community-level approach aims to maintain not only the entire complement of native species in a locale, but also large enough populations of those species to preserve natural genetic diversity and allow natural selection and adaptation of the species to continue. The literature about forest habitat management for all these objectives is extensive, with comprehensive sources of information including books by Hunter (2010), Patton (1992), Bookhout (1994), Payne and Bryant (1994), and Morrison, Marcot, and Mannan (2006).

The species-level and community-level objectives require somewhat different approaches, but they are not necessarily incompatible. Species-oriented management clearly must be based on knowledge of the specific habitat requirements of a species. These are well known for some species, especially game animals for which detailed habitat-management guidelines are available. In other cases (such as little-known species that become rare), extensive research efforts are needed to identify and quantify habitat needs. The results of these studies can be found in the "recovery plans" for endangered species, such as those for the northern spotted owl or the red-cockaded woodpecker. The species-oriented approach is sometimes expanded by defining **guilds** of animal species (groups of species that occupy similar niches and therefore similar habitats). A variation on this idea is to focus on a single species, not because of its exceptional importance, but because its population responses to habitat treatments may indicate the success of management for the guild as a whole. However, enough differences exist among the species within a guild that this has not always proven useful. It is impractical to expect to understand and quantify the habitat needs of all species

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inhabiting a forest area. Therefore, concerns for maintaining overall biodiversity must be met by providing a diversity of habitats.

In either case, habitat management is done principally by controlling **stand structure** (the ages, sizes, and density of trees within a stand) and **forest structure** (the sizes and spatial arrangement of stands within a forest). Stand and forest structure appear to be generally more important than tree-species composition in providing for habitat, although particular species are sometimes important for certain food requirements. Silvicultural treatments can be applied most directly to creating particular *stand structures* for habitat purposes, just as is done to meet other objectives. The principles of designing *forest structures* can partly be drawn from traditional concepts of forest management for sustaining timber production, but additional ideas, some of which have formed the basis for the discipline of landscape ecology, also apply (Forman and Godron, 1986). In situations where individual animals range over very large areas, or when the maintenance of a sustainable population of a species requires a large area (even in cases where individuals have limited ranges), the spatial scale of wildlife management differs from that of timber management. In the latter situation, the land-ownership boundaries determine the extent of management interest. However, to achieve the goals of providing habitat for populations with large land requirements, stands should be treated in the context of the regional landscape, regardless of ownership lines. This presents one of the more challenging aspects of forestland management, requiring economic, social, and political innovations to coordinate efforts. Under almost any circumstances, desirable patterns of landscape diversity represent long-term goals toward which foresters can work, but they are not patterns that can be created in a few years or even a few decades.

Habitat Elements Within Stands

Species in a forest ecosystem are linked together in a food web through which the sun's energy is transferred from producers (plants) to herbivores, carnivores, insectivores, and decomposers. All animals require food, shelter, and water from their habitat. Manipulation of forest vegetation affects food supplies directly for herbivores and decomposers, and indirectly for other species. It affects shelter directly for all species, and may influence water availability in some cases. It is useful to sub-divide habitat needs further into a set of habitat elements that can be controlled by silvicultural operations (Healy, 1987). Wildlife biologists associate the various habitat elements with a series of successional stages (Thomas, 1979; DeGraaf *et al*., 1992). One approach recognizes six stages: grass/forb, seedling/shrub, sapling/pole, intermediate-aged forest, mature forest, and old growth (Fig. 24.1). These stages are defined primarily by vegetation structure, but they are closely related to the developmental stages of stand dynamics discussed in Chapter 4. The occurrence of each habitat element within a stand in different developmental and structural stages, and the control of each element by silviculture, are considered in the following sections.

Habitat as a Source of Food

Food: Browse

Browse consists of the buds, twigs, and leaves of woody plants. It serves as a food source throughout the year for such species as deer, elk, moose, hares, beaver, and grouse, and it is particularly important during the dormant season when other foods are unavailable. Twigs of hardwood species generally have higher nutrient content and are more palatable than those of conifers. Likewise, early-successional species, such as aspen and willow, are more palatable than late-successional, such as beech and oak, primarily because later-successional species include more chemicals, resins, gums, and toxins. Juvenile or young growth is more palatable than older growth for the same reason. The presence of hardwood browse is especially important where the dominant species are pines or spruces, which are rarely eaten; other conifers, such as firs, hemlocks, and the "cedar" species (*Thuja*, *Chamaecyparis*, and *Juniperus*), produce more palatable browse. Browse is useful to most animals only within about 6 ft (2 m) of the ground, although grouse and moose feed at higher levels within the crowns. Thus, availability of browse is greatest during the stand-initiation stage, when shrubs and tree regeneration form dense stands, often comprising a disproportionate amount of pioneer and early-successional vegetation that have leaves that are lower in unpalatable tanins and phenols and that have lower resin and gum content and lignins. This makes the vegetation more palatable for insect larvae as well, which in turn attract animals that eat the insects.

As the canopy of a young stand rises, the edible twigs grow out of reach of most animals, and browse becomes non-existent for animals on the ground as the stand enters the sapling/pole stage. This is not the case for insects that can climb or fly to the foliage. The persistence of habitat with plentiful browse is determined by the rate of height growth of regeneration. In areas with abundant precipitation, dense stands of regeneration tend to develop quickly, and height growth is rapid. In such areas of the Pacific Northwest and in eastern North America, browse production reaches a maximum 5–10 years after a disturbance and then declines rapidly. On drier areas, such as in the Rocky Mountains, the stand initiation stage is prolonged as seedlings slowly

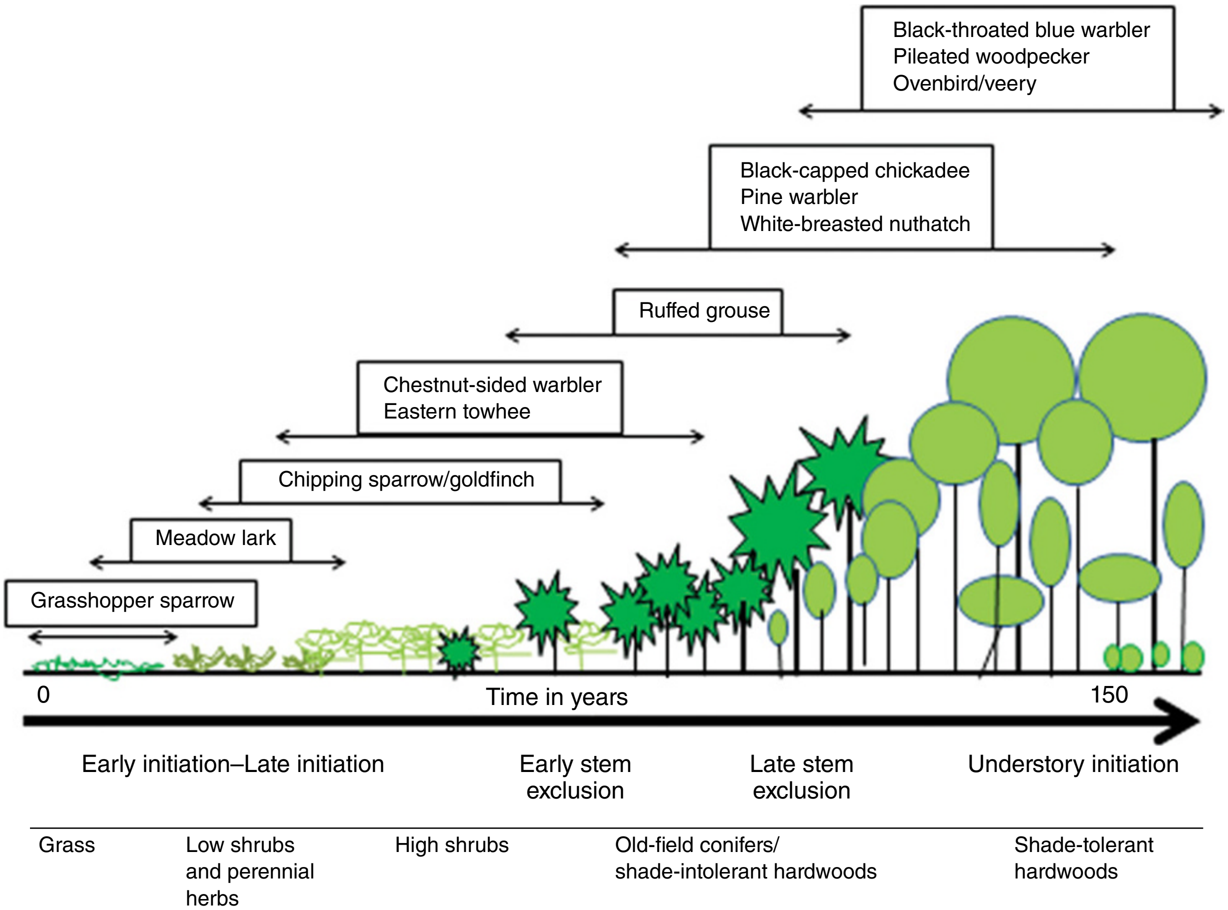


Figure 24.1 A relay floristic model of old-field forest succession and wildlife habitat for an American eastern hardwood forest. Successional stages used by wildlife biologists for describing changes in forest structure are depicted (Thomas, 1979), and their approximate relationship to stand developmental stages described by Oliver and Larson (1990). Relative abundance of different habitat elements is shown for each stage for different bird species; these are meant only to indicate general trends, and do not necessarily apply to all forests types or wildlife species. *Source:* Mark S. Ashton.

colonize a disturbed area, so browse habitat may persist up to age 25. After closed canopies develop, browse production remains low until a woody understory becomes established again in the understory-reinitiation stage, and then develops further in the gaps that occur in old-growth stands. However, the high-density early seral browse that occurs during stand initiation generally does not redevelop in the understory.

The shrub and seedling growth response to any cutting of the overstory is proportional to the amount of canopy removed. Any harvest method that removes all or most of the overstory (clearcutting, seed-tree, coppice, heavy shelterwood cutting, selection cutting using large groups or patches) will provide abundant browse. Thinnings can serve to increase the establishment of a woody understory, but they would have to be heavier than is usual for timber production to obtain an appreciable response. Thinning is more successful in producing browse habitat in stands of species with sparsely foliated crowns, as in pine stands in the southeastern US. The usefulness of areas for browse production can be extended by periodically cutting back or burning young stands as they grow out of the stand-initiation stage. This method will favor sprouting hardwood tree species and shrubs, but germination of new seedlings will occur as well. This technique is commonly used to maintain patches in the shrub/seedling stage in regions where the landscape is dominated by mature forests.

Food: Herbage

Herbaceous vegetation (or **herbage**) includes the leaves, stems, rhizomes, and roots of non-woody plants. These are generally rich in nutrients and are highly palatable to many herbivores. The availability of herbaceous foods is similar to that of browse, being most abundant in the stand-initiation stage. This kind of food is of such importance that wildlife biologists recognize a distinct grass/forb stage as the first following a major disturbance, even though it is often very brief. Herbage declines even sooner than browse, as tree seedlings and shrubs

form a closed canopy and shade out the herbaceous plants. Thus it is difficult to maintain both good browse and good herbaceous foods in the same stand without repeated treatments. In many cases, skid trails and log landings may provide the only areas not dominated by woody plants. It is good to take advantage of them by sowing mixtures of seed of herbaceous plants especially chosen for their wildlife food value.

The grass/forb stage may last only 1 year in areas with prompt tree regeneration, but it can persist for many years in drier areas where woody plants are slow to become established. Herbage develops again in moderate amounts in the understory-reinitiation and old-growth stages, but will be composed of shade-tolerant species that will differ from those of the grass/forb stage. Mowing can sometimes be used to prolong the herbaceous stage, but it will tend to favor sprouting woody plants if they had already become established prior to treatment. The most efficient method for maintaining herbaceous vegetation is the use of prescribed fires, either on a frequent basis or timed in the summer so that the roots of woody plants are killed. This can be accomplished either in open areas or beneath canopies. It is most easily done in areas with prolonged drought, such as in ponderosa pine stands, where partially closed canopies and frequent light fires naturally maintain grass understories in mature stands. In the southeastern US, fires are regularly used in the understory of pine stands to maintain either browse or herbage, depending on the frequency and season of burning (Stransky and Harlow, 1981). Winter burns timed at 3–5-year intervals are used to favor browse production for deer, but summer burns at 1–2-year intervals are used to produce herbage for quail and turkey (Fig. 24.2).

Interestingly and as could be predicted, numerous studies have shown that herbivores can impact and shape the nature and composition of their vegetation. With high deer populations, browsing pressures change the composition and amount of browse to those species that are the most unpalatable (Waller and Alverson, 1997; Augustine and McNaughton, 1998; Schmitz, Hambäck, and Beckerman, 2000). More recently, studies have demonstrated that the presence of predators not only regulates herbivore populations and therefore their impact on plant composition and abundance, but also herbivore behavior (Schmitz, 2008; Hawlena *et al*., 2012). This is because the nature of predator behavior can influence the kind of impact herbivores have on plant composition and productivity. For example, active and roving predators can cause herbivores to simplify plant species diversity and increase net primary productivity, but sit-and-wait predators can cause the opposite effects (Schmitz, 2008). This suggests that the nature of plant composition, growth rate, and abundance is not regulated by just the numbers of herbivores, but by how they behave with the threat of different kinds of predators. Therefore, silvicultural treatments designed to create more herbage for herbivores need to account for the nature and presence of the predator.

Food: Mast

Mast is a term used for the fruits and seeds of trees and shrubs. A distinction is made between **hard mast** (nuts and seeds) and **soft mast** (berries and other fleshy fruits). In boreal and temperate zones, soft mast is produced by early-successional species of many genera, including *Prunus*, *Sambucus*, and particularly *Rubus*. In later developmental stages, most of the berry production occurs on shade-tolerant understory shrubs, with relatively few overstory trees producing this kind of food. In contrast, many overstory tree species, such as oaks, hickories, chestnut, and beech, produce nuts that are among the most important foods in the diet of many animals; conifer seeds also contribute to these hard mast foods (McShea and Healy, 2002). This distinction cannot be made in the tropics, where both fleshy fruits and nuts are common in main-canopy tree species.

The cycle of fruit production roughly coincides with patterns of browse production, being greatest in early-successional vegetation but declining rapidly as the tree canopy develops. During understory reinitiation, a different set of fruit-producing shrub species develops in the understory. In general, silvicultural treatments affect fruit production in ways similar to browse, but with a somewhat longer delay after cutting or burning (Perry *et al*., 1999). A fruiting model for an eastern deciduous forest predicts soft mast production from early-successional plants to peak during years 1–9 after an overstory removal (one-cut shelterwood), then from years 10–60 it would be low, and then increase with late-successional understory species after 70 years (Reynolds-Hogland, Mitchell, and Powell, 2006). The importance of these foods for birds in particular has, in the past, led wildlife biologists to introduce exotic species of berry-producing shrubs, such as multiflora rose and autumn olive, into North America, but it is generally preferable to work with native species. It is likely not a coincidence that many of these species were introduced along roadsides and waysides at a period of second-growth forest development when many native early-successional soft mast species had died or were absent. Stem exclusion was the widespread dominant stage of stand development in the 1930s to the 1950s. This was a time when the Soil Conservation Service was busy stabilizing soil cover and introducing new roadside trees and shrubs for new highways, waterways, and shelterbelts.

Many long-lived main canopy tree species do not produce nuts until they are several decades old, especially if they grow in dense stands where crown expansion is restricted. As trees become sexually mature and crown

(a)

(b)

Figure 24.2 Understory treatments in loblolly pine stands on the Santee Experimental Forest in South Carolina. **(a)** Untreated hardwood understory. **(b)** A spring fire is used to produce herbaceous foods. *Source:* **(a, b)** Mark S. Ashton.

sizes increase, large nut crops are produced and are widely used by both tree-dwelling and ground-dwelling animals. One advantage of nuts as a food is that they have a long shelf life, remaining usable for many months, either on the tree or the forest floor, or stored in caches by animals. Thus, they can be eaten during the dormant season, when other foods are in short supply. Animals that are highly dependent on nuts include small mammals (mice, chipmunks, voles, and squirrels), as well as turkeys, jays, bears, and deer. The supply of hard mast is a limiting factor controlling winter survivorship in many of these species. Abundant nut crops are produced periodically in "mast" years by many of the mast-producing species, particularly the oaks, with very low production during intervening years. The intervals between mast years strongly affect the cycles in animal populations (Ostfeld, Jones, and Wolff, 1996).

Stand density affects nut production in patterns similar to those for stem volume growth; individual-tree nut production is highest with heavy thinning, but stand-level production is little affected by thinning as long as large gaps are not made in the canopy. This is true if all

trees in a stand are mast species. Thinning mixed-species stands to favor mast-producing species will clearly increase nut production at the stand level; in doing so, it is preferable to maintain a diversity of mast species.

Habitat as a Source of Shelter

Shelter: Cover

Cover consists of any vegetation that shelters wildlife from predators (**escape** or **hiding cover**) or climatic extremes (**thermal cover**). All forest vegetation, living or dead, provides some benefits of shelter, but the high densities of woody stems that usually occur in young stands provide the best cover for many animal species. If an herbaceous stage occurs at the earliest part of stand initiation, escape cover will be poor or absent for most species. In fact, this condition provides important hunting habitat for raptors precisely because the cover for small mammals is intermittent. The dense shrub/seedling stage then becomes very important as cover for small mammals and birds, and once the height reaches about 6 ft (2 m), it is also useful to large mammals. The value of young stands for cover persists longer than for browse, forage, and soft mast, lasting into the sapling/pole stage. As stem density is reduced from natural mortality or thinning, the value for cover is reduced. When an understory of shrubs and shade-tolerant tree species develops in mature stands, escape and nesting cover will be present for some species of ground- or shrub-nesting birds and small mammals.

Thermal cover coincides with escape cover for many animals. Any closed canopy will reduce solar heating during the day and reduce radiational cooling at night. However, for large mammals in particular, the escape cover in young stands does not provide a sufficiently dense canopy for thermal cover purposes. Conifers have particular importance as thermal cover because they retain their sheltering effect during the winter, reducing windchill and radiational cooling, and also creating lower snow depths by intercepting much of the snowfall. This allows deer and elk to conserve energy and have better mobility, as well as to more easily find browse and nuts on the forest floor. Maintaining nearly closed canopies in conifer stands is particularly important in forests that are dominated by deciduous species. In cold climates, deer concentrate in such areas, known as “deer yards” (Mysterud and Østbye, 1999). Therefore, thermal cover also creates what has been referred to as “settling stimulus,” where animals persist in one location for a long period of time. In the case of herbivores, such as elk and deer, this can induce heavy localized browsing with only a few animals. Reducing animals by a cull would thus be misguided. Instead, breaking up the habitat cover or “settling stimulus” by some kind of treatment would be more appropriate (Barrett and Schmitz, 2013). An alternative would be to reintroduce a top predator, if absent, although this may be politically unacceptable.

Shelter: Cavities, Dens, and Snags

Cavities in living and dead trees are of great importance for bird and mammal species as shelter for escape, sleeping, and rearing young. As stands develop, some trees begin to decline in vigor owing to competition, and some suffer injuries from snow, ice, wind, and fire. Poor vigor and broken branches allow invasion of decay insects and fungi, leading to the formation of decay cavities in living trees. Most mammal dens occur in cavities in living trees (**den trees**), but birds make more use of cavities in standing dead trees (**snags**) (Raphael and White, 1984). In addition to these decay cavities, woodpeckers excavate their own cavities, mainly in living trees infected with heart rot, which are subsequently used by other species.

Stands typically produce dead trees in the process of self-thinning, but trees dying from suppression in early stages are too small to provide cavities useful for any except the smallest animals. Smaller birds and mammals can use trees that are only 10 in (25 cm) diameter at breast height (DBH), but many species require trees of at least 20 in (50 cm). Larger snags tend to be used simultaneously by a number of birds and mammals. Thus even-aged stands do not form the most valuable den trees and snag trees until they reach the stage when large dominant trees decline in vigor and die. The density of cavities in old, even-aged stands may not differ greatly from that in old-growth stands in many forest types (Table 24.1).

Scarcity of snags can limit the size of bird populations in intensively managed even-aged stands. The most direct approach to maintaining cavities throughout stand development is to retain a number of snags during thinning and during harvest of mature stands. Estimating the density of snags required to support maximum populations is complicated by the different minimum size requirements of bird species and their territorial behavior, which limits the usefulness of groups of snags for some species. Appropriate densities have been studied for a number of bird species (Tubbs *et al*., 1987; Thomas, 1979), and, although some variations exist, fairly consistent guidelines of retaining two to five snags/acre (5–12/ha) have been proposed for many forest types in North America (Hunter, 2010). Estimates of large den-tree requirements for mammals are lower, ranging from 0.1–1.0/acre (0.2–2.0/ha). It may be difficult in practice to meet density goals during timber marking because of clumped distributions of cavity trees and random variation in the actual occurrence of cavities in trees of similar species and size. It may often be adequate to retain dead trees (unless it is hazardous to forest workers to do so) and den trees with actively used cavities. This will supply habitat needs but will not result in a large proportion of the living stand basal area being cull trees (Healy, 1987).

Table 24.1 Snag densities per acre by size class and by different managed and unmanaged forest types in North America. Size classes vary by study.

Forest type	Size classes: Small	Medium	Large	Condition
Ponderosa pine (CA)	0.7	2.2	1.4	Unmanaged National Forest (mature)[1]
Ponderosa pine (CA)	2.8	3.8	0.5	Private industrial (even-aged managed)[1]
Sierra mixed conifer (CA)	2.7	2.6	1.7	Unmanaged National Forest (mature)[1]
Ponderosa pine (CA)	2.1	1.5	0.3	Private industrial (even-aged managed)[1]
Pacific-side Douglas-fir (OR)	0.3–1.5	0.8–2.1	0.3–0.5	Unmanaged National Forest (mature)[2]
Aspen (MI)	26.8 across all size classes			Private industrial (even-aged managed)[3]
Northern hardwood (MI)	29.3 across all size classes			Unmanaged National Forest (mature)[3]
Northern hardwood (MI)	31.6 across all size classes			Private industrial (even-aged managed)[3]
Northern hardwood (Quebec)	29.5	6.1		Unmanaged Provincial land (mature)[4]
Northern hardwood (Quebec)	18.6	3.7		Provincial land (all-aged managed)[4]
Northern hardwood (Nova Scotia)	66.2	10.2		Provincial land (mature)[5]
Upland hardwood piedmont (SC)	35.3 across all size classes			Private (even-aged unmanaged)[6]
Pine plantation piedmont (SC)	12.0 across all size classes			Private (even-aged managed, young)[6]
Pine plantation piedmont (SC)	15.1–25.8 across all size classes			Private (even-aged managed, mature)[6]
Pine hardwood coastal plain (FL)		6.8		Private (even-aged unmanaged, mature)[6]
Pine plantations coastal plain (FL)		7.2–10.7		Private (even-aged unmanaged, mature)[6]
Pine coastal plain (FL)		2.6		Private (even-aged managed, young)[7]
Bottomland hardwood (LA)		6.4–11.0		Private (even-aged unmanaged, mature)[8]

1) Warbington and Beardsley, 2001. [Size class defined as: small, 10–15 in (25–40 cm) DBH; medium, 15–30 in (40–70 cm) DBH; large, >30 in (70 cm) DBH.]
2) Ares, Bright, and Puettmann, 2012. [Size classes: small <20 in (50 cm) DBH; medium 20–40 in (50–100 cm) DBH; large >40 in (100 cm) DBH.]
3) Monfils *et al.*, 2011. [Measured snags all greater than 4 in (10 cm) DBH.]
4) Doyon *et al.*, 1999. [Size classes: small, 4–10 in (10–25 cm) DBH; medium, >10 in (25 cm) DBH].
5) Moroni and Ryan, 2009. [Size class: small 3.5–8 in (9–20 cm) DBH; medium >8 in (20 cm) DBH.]
6) Moorman *et al.*, 1999. [Measured all snags greater than 4 in (10 cm) DBH.]
7) McComb *et al.*, 1986.
8) McComb and Noble, 1980.

During harvests, the practice of leaving snag and den trees (often simply referred to as “wildlife trees”) has become standard in many areas (Fig. 24.3), but it may only be a temporary solution to the problem in any one stand. Unless the snags are of large size, they may decay and fall before the surrounding stand is mature enough to produce a next set. If stands are managed on a rotation that does not produce large trees, a new set will never develop. Providing for future generations of snags can be accomplished by retaining not only current snags, but also an additional set of living trees, with some having large branches or heart rot which makes them likely to form cavities. These are just the sort of trees usually removed in partial cuttings. This would fit rather easily into selection-system management by allowing some trees of this kind to remain after they had reached the final diameter goal for timber production, thus providing a constant supply of den and snag trees.

With even-aged management, crown thinnings that intentionally leave over-topped trees that would be considered long-lived pioneers is one way of promoting future cavities. Species such as red maple exhibit substantial branch dieback which later become cavities. In addition, the retention of a set of living trees that are past final harvest is sometimes referred to as “green-tree retention” in order to distinguish it from snag retention (Franklin and Spies, 1991). This term may convey a rather specific practice in areas where clearcutting and planting is the standard regeneration method used, such as in the Pacific Northwest, as depicted in Fig. 24.3. However, living trees are retained in a great variety of densities and spatial patterns in other areas, so it is not very useful as a

Figure 24.3 Openings created by variable-retention methods, leaving individual and groups of mature trees standing; it is aimed at hastening the redevelopment of old-growth habit characteristics following the harvest of a Douglas-fir/western hemlock stand in Oregon. *Source:* US Forest Service.

general term. The key point is that a set of mature **reserve trees** are maintained well into, and possibly to the end of, the next rotation. In some cases, they may be reserved after clearcutting and planting in others, they may remain at the end of a series of cuttings that are part of the irregular shelterwood method. The general concept of retaining reserve trees from one rotation to the next can be adapted to the objectives of maintaining future den and snag trees, producing sawtimber trees, or a combination of both in the same stand (see Chapter 11).

Under some circumstances, as for wood ducks and owls, nesting boxes have been employed to substitute for natural cavities. Methods have also been developed to create snags by killing trees with herbicides in ways that make the decaying tree most useful to cavity nesters.

These are solutions to the problem of providing cavities within a single-aged stand, but they are not the only approach. These needs can also be met at the forest level without any particular silvicultural treatments by maintaining a spatial arrangement of stands such that old stands with cavity trees are adjacent to young stands (see section in this chapter on landscape elements).

Shelter: Coarse Woody Debris

The recognition that **coarse woody debris** or **dead wood** was the food base and carbohydrate supply for many small forest animals and decomposers, either directly or indirectly, grew to widespread acceptance about 30 years ago (Harmon *et al*., 1986; Hagan and Grove, 1999). It can be left in the form of logging slash and fallen trees and branches to serve an important habitat function (Brown, Reinhardt, and Kramer, 2003). Cavities in large fallen logs provide the same kind of shelter as do those in standing trees, but accommodate species that do not fly or climb very high, such as red foxes, weasels, salamanders, and turtles. The branch-sized material that makes up the majority of logging slash also has value as escape cover for small animals, substituting for dense seedling cover during the earliest stages of stand development (Butts and McComb, 2000). Deep slash can inhibit the movement of large animals such as deer and elk, but this problem can be remedied by providing lanes cleared of slash throughout harvested areas. Most studies report that the highest amounts and largest sizes of dead wood are in old-growth stands as compared to stands managed under selection systems, and least amounts are reported for even-aged intensively managed plantation systems (Sturtevant *et al*., 1997; Goodburn and Lorimer, 1998; Loeb, 1999; Butts and McComb, 2000) (Table 24.2). However, correlation between dead wood and its actual association with animal populations can be very vague and non-significant in some forest regions (Bowman *et al*., 2000), whereas others show strong positive relationships (Loeb, 1999).

Dead wood of all sizes, both standing and down, also provides the main food source for fungi, insects, and other decomposer organisms (Fig. 24.4). These in turn are the food of many animals higher on the food chain. Thus forgoing slash burning or other disposal methods will benefit many species, but this must be

Table 24.2 (a) Amounts of dead wood (number per acre) by size class on the forest floor for different forest types and by kind of management. (b) Amount of coarse woody debris for different age classes (m^3/ha).

(a)

Forest type	Size class			Condition
	Small	Medium	Large	
Ponderosa pine (CA)	5.7	7.2	0.1	Unmanaged National Forest (mature)[1]
Ponderosa pine (CA)	11.3	8.3	1.9	Private industrial[1]
Sierra mixed-conifer (CA)	5.7	6.8	2.4	Unmanaged National Forest (mature)[1]
Sierra mixed-conifer (CA)	13.0	17.4	3.1	Private industrial[1]
Aspen (MI)	35.8	0.8	0.1	Private industrial[2]
Northern hardwood (MI)	39.5	21.2	2.6	Unmanaged National Forest (mature)[2]
Northern hardwood (MI)	32.6	3.6	0.3	Private industrial[2]

For Michigan forest types: size classes defined are: small, 4–10 in DBH; medium, 10–20 in DBH; large, >20 in DBH.
For California forest types: size classes defined are: small, 10–15 in DBH; medium, 15–30 in DBH; large, >30 in DBH.

(b)

Forest type	Age class			Condition
	Young	Mature	Old growth	
Pacific Northwest (Cascades)	248	148	313	Douglas-fir, unmanaged National Forest[3]
Boreal (Ontario, Canada)		17.8		Spruce–fir, unmanaged[4]
Boreal (Ontario, Canada)	342.6	160.8		Mixed-wood unmanaged, young (1 year post burn)
Boreal (Ontario, Canada)		105.2		Deciduous, unmanaged

1) Warbington and Beardsley, 2001. [Size class defined as: small, 10–15 in (25–40 cm) DBH; medium, 15–30 in (40–70 cm) DBH; large, >30 in (70 cm) DBH.]
2) Monfils *et al*., 2011. [Measured snags all greater than 4 in (10 cm) DBH.]
3) Spies, Franklin, and Thomas, 1988.
4) Pedlar *et al*., 2002.

balanced against the need for protection against fire and insect pests that breed in the slash (Stephens and Moghaddas, 2005).

Water Bodies and Riparian Zones

All animals depend on water for its life-giving sustenance. Many animals indirectly rely upon it for food and shelter. Many more animals are defined by its presence, and depend entirely upon it for habitat, food, and protection. This all means that wherever there is water there is wildlife. Its presence is undoubtedly the most important factor influencing habitats of the drier climates of the world. In fact, understanding the nature of water and how it collects and moves off a landform is the base template for building a reserve system within a managed forest. Water serves to accentuate contrasting vegetation types, it serves to increase herbage and browse as a source of food, and it serves to increase canopy cover as a shelter. The nature of a water body within a stand can be categorized by its permanence, its movement, and its size.

Streams and Riparian Zones

The vegetation structure in **riparian areas** surrounding streams, swamps, and pools affects the habitats of both aquatic and terrestrial animals. Aquatic food webs in small streams are based on the input of leaves and other detritus from the surrounding forest. Microbial decomposers and aquatic invertebrates (particularly insect larvae) feed on the detritus and become food for most fish and amphibian species. In larger streams and ponds with slower currents and more sunlight, the photosynthesis of algae and shoreline plants plays a more important role in the food web.

Figure 24.4 Downed and standing coarse woody debris in an old-growth Norway spruce–white fir forest in Bosnia-Herzegovina comprising about 66,000 boardfeet/acre (383 m^3/ha) of downed material. The study by Motta *et al.* (2008) dated some of the trees to be over 450 years old. *Source:* Italian Society of Silviculture and Forest Ecology. Reproduced with permission from R. Motta, Italian Society of Silviculture and Forest Ecology.

It is usually desirable to maintain shading over streams in order to keep the water cool, principally because the capacity of water to absorb oxygen and other gases *decreases* with warming. This is best done by retaining all or some trees that are tall enough and appropriately placed to shade the water. Such action is consistent with retaining filter strips of forest floor material and dense vegetation along the streams (see Chapter 23). Maintaining cool temperatures is most important in trout and salmon streams, because many of these species have rather limited tolerance for high water temperature and low dissolved-oxygen content. In some situations, moderate opening of the canopy may improve fish habitat conditions by increasing photosynthetic levels in larger water bodies or by raising water temperatures in very cold, high-elevation streams, but in most cases maintaining a nearly complete canopy provides the best conditions.

A principal objective of maintaining dense riparian vegetation is to prevent particulate matter and dissolved nutrients from reaching streams. Paradoxically, some of the products of erosion are beneficial, although only when present in moderate levels close to that which occurs in unmanaged ecosystems. Some of the chemical nutrients that are leached into streams are necessary for the organisms that live there. The same is true of limited amounts of colloidal clay that provide base exchange capacity. However, excess sediment can cover gravel areas and fill in deeper pools, degrading habitats for both fish and insects, and excess nutrients may bring about the problems associated with eutrophication.

Streamside vegetation is also important as a source of large woody debris that falls into streams, creating deep pools with slower current. Pools provide escape and resting cover for fish by protecting them from predators and allowing them to maintain their position with low energy expenditure. However, fast-moving riffle areas provide the best habitat for insects, and therefore the best feeding habitat for fish. Optimum habitat for some species includes a fairly large proportion of stream area in pools, such as in mountain streams in Colorado where a pool:riffle ratio of 50:50 is considered most desirable for trout habitat (Moore *et al.*, 1987). Pools tend to be in relatively short supply in smaller streams, and it may sometimes be desirable to install logs across streams to create additional ones. However, it would be carrying things to excess to use these benefits as an excuse for carelessly dumping tree-tops and other debris into streams. Excessive amounts of undecomposed organic matter in still ponded waters can reduce dissolved oxygen almost completely and render the waters essentially lifeless. It is better to avoid felling trees into streams or ponds in the first place, since pulling the slash or logs out can do damage to stream banks.

Terrestrial animals spend a disproportionate amount of time in riparian zones, largely because of a daily need for water, but also because the vegetation of these areas is often distinct from that of the surrounding forest. Along larger streams, riparian vegetation may consist of entirely different tree, shrub, and herbaceous species. This contrast is greatest in coniferous forests in dry climates, where riparian zones often contain the only deciduous tree species in the region.

The key point about riparian vegetation management for terrestrial animals is that any habitat element will be more valuable if it exists near water rather than elsewhere. Maintaining a riparian area as mature forest provides cavities and dead wood and is compatible with the need for a filter strip and stream shading. The width of a special habitat management zone for terrestrial animals may be larger than is needed for the water-filtering function. This would depend on the prevalence of water bodies and the degree of contrast with non-riparian vegetation in the area. Harvesting patches in riparian areas can help to develop food and cover there, in addition to mature forest habitat. This is particularly important for deer-wintering areas throughout the forest region dominated by northern hardwoods, spruce, and fir, where deer congregate in dense conifer stands near streams and wetlands. Providing patches of abundant hardwood browse near these deer yards improves the winter survivorship of deer herds.

Ephemeral Pools and Seeps

Extensive studies over the last 30 years have demonstrated that vernal and seasonal pools and seeps within forest stands can comprise unique and diverse biota that are associated with the timing and presence of water. For seeps, the most obvious association is with ephemeral plants that grow and reproduce during the wet period. Unique populations of plants are associated with seeps in temperate moist forests (Hall, Raynal, and Leopold, 2001; Morley and Calhoun, 2009), but their importance is much more significant in drier and more seasonal forest types of the western US and especially the Mediterranean climate of parts of California (Rudner, 2005). Identifying seeps and protecting them with buffers of at least 50–80 ft (15–25 m) from timber harvests is an important conservation practice.

In the case of pools, the most obvious association is with amphibians (frogs and salamanders in particular), and the lack of fish that predate their eggs. Studies show that to protect the integrity of the amphibian populations within a vernal pool, upland buffers of intact forest canopy need to be at least 575 ft (175 m) away to protect the majority of the population (Semlitsch, 1998, 2000; Faccio, 2003). Semlitsch and Brodie (2003) reviewed studies for a variety of amphibians and reptiles that showed that the buffers necessary to protect 95% of animals ranged between 400–1000 ft (130–300 m).

The most important controlling factor of upland buffers around a pool was canopy cover. An eastern US study by Rothermel (2004) showed that less than 15% of toads and salamanders released in an open meadow reached the cover of an adjacent forest 160 ft (50 m) away. The nature of canopy cover and groundstory litter can also determine both the diversity and abundance of amphibians, with hardwood litter and cover being a better habitat than conifer because of its greater depth, greater surface roughness and heterogeneity, and higher nutritional quality (DeGraaf and Rudis, 1990; Belasen *et al.*, 2013). Although studies have shown that rodents were not found to either increase or decrease in population or diversity with the presence of vernal pools (Brooks and Doyle, 2001), their burrowing activities greatly improve amphibian habitat (Faccio, 2003). Thinnings within buffer zones have not been studied well, but what results exist show they are inconsequential as long as the groundstory remains largely undisturbed and the canopy cover largely intact (Semlitsch *et al.*, 2009). Forest harvesting that is tailored toward regenerating a stand will have an impact but this can be mitigated by careful planning that leaves extensive buffers around pools, leaves residual canopy cover with reserves, protects the surface cover, promotes downed woody debris and leaves, and protects the root channels associated with stumps (deMaynadier and Hunter, 1995; deMaynadier, 1998, 1999; Marsh and Trenham, 2001). In a model analysis based on a set of forest cover and manipulation experiments in Maine, Missouri, and South Carolina, Harper, Patrick, and Gibbs (2015) reported that, although intensive forest clearcutting can significantly decrease amphibian populations locally within a managed landscape, there are very low chances for extinction. Intensive site preparation, burning, and establishment of conifer plantations managed on short rotations can all have significant long-term detrimental impacts on both amphibian and reptile populations (deMaynadier and Hunter, 1995; Perry, Rudolph, and Thill, 2012).

Interestingly, in northern latitudes where vernal pools are exposed to some direct light at least from one side, and the upland forest buffer remains largely intact, both the amphibian richness and its larval maturation rates increased because of the warmer water and the greater abundance and composition of algae and microbiota as a food source (Skelly, Freidenburg, and Kiesecker, 2002; Skelly *et al.*, 2005). Both the open-canopy specialists and the canopy generalists were present in brighter light regimes as compared to more shaded pools where only canopy generalists were present.

Finally, one group of taxa that can greatly benefit from vernal pools and seeps are birds. The lush vegetation associated with more open pools and seeps provides breeding habitat for many smaller passerines. Pools can

be important feeding grounds for ducks and waders that eat young aquatic vegetation and invertebrates. Ephemeral wetlands and pools can also play critical roles in providing feeding and resting habitat in flyway corridors, particularly in regions where water is limiting (e.g., the Pacific flyway) (Silveira, 1998).

Rivers and Flood-Plains

Much larger water bodies that flow can create their own very open ecosystems. Rivers with flood-plains are a very good case in point. Their primary value to society is to regulate and mitigate downstream effects of flooding and to act as a protective buffer for cities, towns, and farmlands. A important secondary value of these ecosystems is that of wildlife habitat. Systems that are very open in nutrient flow with vibrant sediment movements that both erode and deposit, with successional processes that can be extremely dynamic, are best left alone and should be protected (Sparks *et al*., 1990; Bayley, 1991, 1995).

The periodicity and degree of annual flooding obviously varies, but the vegetation and its successional dynamic can exert a high degree of control by greatly reducing runoff and turbidity, and increasing light levels to promote a high diversity of aquatic plant and animal life upon which many migrant birds are dependent (especially ducks, geese, herons, and waders). Flooding is the most important annual variable that drives both the flow and exchange of nutrients, organic matter, and organisms, upon which plant productivity and watershed integrity are maintained. Any silvicultural treatment to disrupt these factors will lead in the long run to river degradation. Increased sediment inputs and turbidity, often from upstream, has led to large river systems becoming barren de-vegetated wastelands. Most of the offending practices have been related to bad upstream agricultural practice and to poorly planned flood-control measures. Even so, silvicultural practice needs to heed lessons learned from these mistakes. Harvesting in bottomland floodplain forest needs to be done in such a way that it creates extensive protection buffers along oxbows and watercourses, and should be carefully scaled to patches as either selection or irregular shelterwoods. Such openings would release much of the shade-intolerant advance growth (mostly bottomland oaks) as well as promote the release of coppice sprouts. The hard mast of species such as oak is critical for many species of wildlife. The thick early-successional vegetation composition and structure can also provide unique breeding habitat for many passerines and water ducks, as long as vertical structure is in some way maintained (Sparks, 1995; Twedt *et al*., 1999, 2002).

Wetlands: Ponds and Swamps

Wetlands are defined here more narrowly as where water accumulates and often stagnates, and therefore becomes poorly oxygenated. Cypress domes, pine flatwoods and poccosins, cedar swamps, and spruce bogs are all examples (Sun *et al*., 2001). Interestingly, they are often dominated by conifers that are tolerant of poor oxygen and water-logged conditions. For wildlife, the evergreen thermal cover in northern latitudes provides important wintering grounds for deer (Van Deelan *et al*., 1998). As long as silvicultural treatments do not alter the nature of the hydrology, these systems can be managed sustainably for timber by partial harvesting or regeneration methods that create small-scale patches within the wetland itself (Sun *et al*., 2001). In most circumstances, wetlands within forested landscapes should be protected rather than managed, given their more important hydrological function. They also provide a unique composition and structure compared to surrounding upland stands and therefore comprise unique habitat for specialist wildlife species. Thus, it is better to allocate wetland stands to the reserve system within a managed forest rather than to apply silvicultural treatments.

Structure and Composition

Vertical Stand Structure

One stand attribute that is associated with wildlife-species diversity is that of structural diversity in the vertical dimension (Hunter, 2010). Much of the interest in vertical structure has come from studies of bird populations, where it was found that tree crowns are partitioned among species for feeding and nesting at various levels, but any set of tree-dwelling animals will likely benefit (Whelan, 2001; Diaz *et al*., 2005) (Fig. 24.5). Epiphytic plants may also benefit, especially in moist climates where this lifeform is prevalent. High levels of vertical structural diversity are found in old-growth stands where canopy gaps have been created by the deaths of individual large trees. A continuous canopy occurs in some parts of these stands from the tops of the largest trees down to the released understory trees, regeneration, shrubs, and herbs growing in the gaps. This structure begins to develop as soon as old, even-aged stands enter the gap dynamics phase.

The lowest structural diversity is found in even-aged single-species stands, particularly those composed of a relatively shade-tolerant species in which most light is captured in one canopy layer, thus eliminating most understory vegetation. This kind of stand is typified by Norway spruce plantations maintained at high densities. Natural forests with low vertical diversity also occur, including nearly pure stands of lodgepole pine, jack pine, or black spruce, which develop after hot fires. Vertical diversity in even-aged stands is greatest in species mixtures with pronounced vertical stratification among the crowns of the component tree species. However, this structural complexity is largely restricted to the tree and

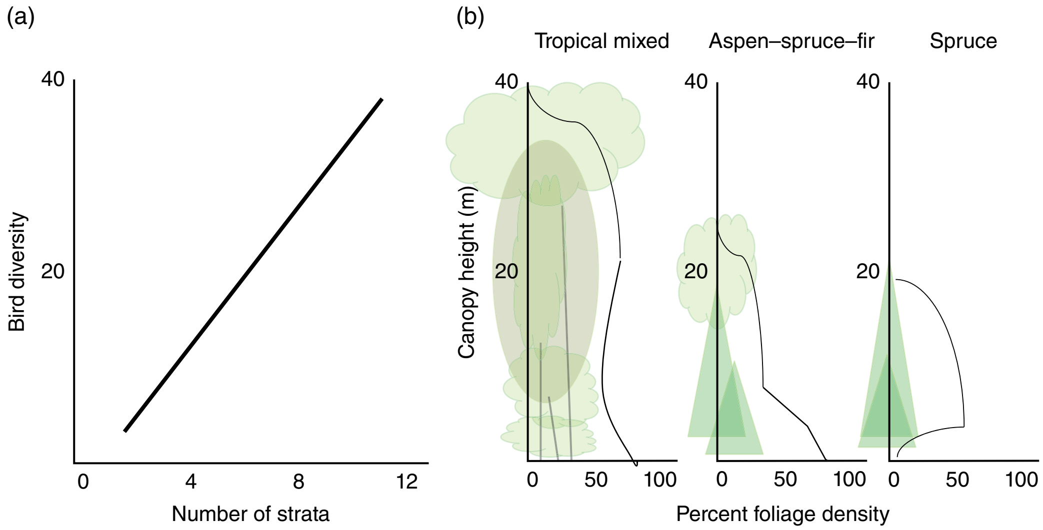


Figure 24.5 Bird diversity in relation to vertical foliar diversity of forests. **(a)** A regression predicting the number of bird species in a forest (vertical axis) from the number of foliar layers (strata) of the forest (horizontal axis). *Source:* Adapted from Hunter, 1990. **(b)** Three example forests with different foliar diversity in canopy height-to-depth ratio of foliage, numbers of strata, and canopy heterogeneity (as measured by evenness). *Source:* Data from Hartley and Hunter, 1998.

shrub layer, and lacks the dense seedling and herbaceous vegetation that grows in the gaps in all-aged or multi-aged (uneven-aged) stands.

The kind of vertical diversity found in old-growth stands can be mimicked in younger stands by the use of single-tree selection or small-group selection to create the equivalent of treefall gaps. However, results differ when the groups are larger in diameter than about twice the height of the main overstory trees (as discussed in Chapters 5 and 13). Cutting in larger groups essentially creates a number of single-aged (even-aged) patches of different ages. This is more than just a fine point of terminology, because these larger groups create patches of early-successional vegetation which have greater similarity to that occurring in large stands than in small gaps.

A very different kind of vertical stratification occurs in two-aged stands, in which younger vegetation becomes established beneath partially closed mature canopies. This occurs naturally after extensive but incomplete mortality from wind or fire, and is a temporary condition. As these stands age, the rapid height growth of the regeneration relative to the mature stand obscures the distinct canopy layering. Some methods of creating this structure were described earlier in this chapter with regard to particular habitat elements; combining thinnings with prescribed burning to produce understory browse and herbage, or maintaining reserve trees after final harvest are ways of combining mature forest overstory with early successional vegetation. The creation of wooded pastures in medieval deer parks in Great Britain and Europe is an early example of this approach. It can be a useful way to mix timber-production and wildlife-habitat objectives, and usually is used to make up for the lack of one habitat type in an area. In some situations, this structure can improve habitat conditions. For example, browse tends to be more useful to deer in shelterwood areas than in clearcuts, because of the partial shelter provided. Although two-aged stands play an important part in habitat management, they do not contain the same kind of vertical structure found in stands of the kind created by selection or irregular shelterwood management.

Tree Species Composition

Although vegetation structure is generally the single most important factor affecting habitat quality, tree species composition cannot be ignored in some situations. The most obvious cases are those in which an animal species is dependent upon a particular tree for food, such as the dependence of ruffed grouse on aspen flower buds, and catkins for winter food in some parts of its range (Gullion, 1984). In other situations, species composition has a broader effect on wildlife species. An important one is that in which native mixed-species stands have been replaced by plantations of a single species. The use of an exotic species would be an extreme case of reducing habitat value, because many native animal species would not be adapted to use it. However, a single native species grown in stands of simple structure across all site conditions could be nearly as limiting (e.g., Douglas-fir, loblolly pine). The use of native tree species adapted to each site type would avoid many of these problems. In areas where plantation forestry is used on a large scale, maintaining a portion of each site type in stands with native tree species (not necessarily reserved from timber management) represents an

important compromise between meeting timber and wildlife-habitat goals.

Another example where composition can make a big impact on the habitat quality of a stand is tree species phenology. Evergreen tree species can provide an added structural aspect to stand habitat. As mentioned in the prior section on cover, evergreen species provide thermal cover during cold periods through insulation and in hot periods through shading. Intimate mixtures of deciduous and evergreen stratified forest, with the evergreens beneath the deciduous species, can greatly accentuate forest structure and vertical canopy diversity.

Finally, certain species of trees in a variety of forest types play a disproportionate role in maintaining wildlife diversity, often as an important source of food during periods when other food sources are absent. It is very important to recognize these tree species and retain them whenever possible. These species are called **keystone** species because so many species of wildlife are dependent upon their survival (Table 24.3). An example of a keystone species is *Ficus*, a tree genus found in many tropical forests that fruits year-round, providing an important source of nutritious food for most frugivorous birds and bats at times when no other plants are fruiting.

The Use of Tree Reserves within Regenerating Stands

In even-aged methods of regeneration, the use of reserves is the only way of retaining elements of the original forest structure and species composition within a young regenerating stand. Reserves are frequently used to provide den, mast, and shelter for wildlife in young regenerating open-stand environments. Doing this can modify habitat enough to allow certain species of birds and mammals of mature forest to utilize early-successional forests. Examples are: (1) retaining hard-mast trees as a food source for rodents (squirrels); (2) retaining large den or wolf trees for arboreal cavity-nesting birds and mammals; (3) retaining groups of evergreen trees for thermal cover and shelter from the open conditions of full sun; (4) retaining a range of smaller size classes including trees species that are likely to exhibit dieback or become snags; (5) retaining large canopy trees with various kinds of vertical structure and platforms that can provide habitat for nesting birds, roosting sites, and perching places.

Table 24.3 Almost all tree and shrub species have a wildlife value. Certain species of trees and shrubs can be defined as keystone or foundation species within forests of North America.

Tree/shrub	Functional value
Aspen	A very important forage for ungulates, birds, and many insects
Cherry	Important nectar source, berries, migratory birds, leaves important for insect herbivory
Cottonwood	An important riparian habitat tree
Hemlock	Thermal cover and habitat for resident mammals and birds in winter; breeding bird habitat
Oak	Acorns are a basic food source for many species of mammals, birds, and insects
Salix	An important riparian forage for ungulate and herbivorous insects
Viburnums/ elderberry	Flowers are an important source of nectar, fruit are widely eaten by birds

Source: Mark S. Ashton.

Protecting Old-Growth Habitat and Structure

Sustained-yield timber management will generally not provide old-growth habitat unless special accommodations are made. Old-growth habitat is distinctive because it includes particular habitat elements (den trees, snags, and fallen logs, all of large sizes) and particular stand structural characteristics (mature canopy with gaps and complex vertical canopy structure). This kind of structure was first described in detail for the Douglas-fir/western hemlock forests of the Pacific Northwest (Franklin and Spies, 1991), but similar structures with somewhat different dimensions have been described for forests elsewhere. This structure first develops naturally 150–250 years after a major disturbance in many forest types. It is important to note that not all old-growth stands look like this, particularly in drier, more open, forest and woodland types, and in forests with predictably short disturbance return intervals. Also, it is important to recognize that even prior to colonization in the 1700s, the native peoples had impacted North America's forests with fire and cultivation for thousands of years, leaving little as untouched old growth.

However, given these considerations, some of these individual old-growth structural elements can be created in a variety of ways. One way in managed stands is to retain older reserve trees within normal timber rotations. An alternative is to manage a portion of stands on longer rotations, so that they pass the age at which old-growth characteristics develop, and then maintain that condition for a significant period. This extended-rotation approach can be used with either single-aged, multi-aged, or all-aged stands (in the latter case, by setting a large final-diameter goal). Also, another option is to strategically create a protected-areas reserve system of stands that will develop old-growth structures surrounded by stands of the managed forest. All three strategies to retain old-growth characteristics within a managed forest can be used simultaneously if so desired.

Maintaining a certain portion of the forest in old-growth structures is clearly an important part of efforts to establish a system of protected reserves on all site types in each region. Old-growth stands are among the areas least disturbed by humans and therefore represent logical choices for the core areas for such reserves. Younger forests dominated by native species are also important for these conservation efforts, especially where old-growth stands are rare or entirely absent. Thinning or selection harvesting in younger stands may be useful to speed the development of old-growth structures, after which they would be left unmanaged. Reserves represent a community-level approach to preservation of natural processes, and provide habitats for the plant, animal, and microbial species for which habitat needs have not been determined, or for those species that have not even been identified. Other methods of creating old-growth structural features in managed stands are not a replacement for reserves; rather, they are a means of expanding elements of old-growth habitats beyond reserve areas.

The Other Side of the Stand Interior: Edges

Sustained timber yield depends on a balanced stand-age distribution, but not on the size and location of stands, although these can affect logging efficiency and therefore financial yield. Habitat conditions have a fairly complicated dependence on these factors. Many wildlife species are more common near edges where different plant communities meet. This phenomenon, known as the **edge effect**, was first described by Leopold (1933) for game animals. Most game species do not actually use the edge itself but need access to two or more habitats on a daily basis; thus, they make much greater use of habitats near edges. For example, deer and elk need the youngest stages for browse and herbage, but require older forest for cover; the use of open areas by these animals decreases sharply with distance from escape or thermal cover. Ruffed grouse require the shrub/sapling stage for summer cover to raise their newly hatched broods, but sapling/pole stands are used for cover at other times, and older stands are needed for feeding on browse and mast from within the tree crowns. The importance for many species of having feeding areas adjacent to cover can be seen in the use of the word **covert** in wildlife management. This word originally referred to any area providing cover (Leopold, 1933) but has come to mean any area where at least three habitats meet in an edge (Hunter, 2010). Two other words, **contrast** and **juxtaposition**, are also used interchangeably when managing edge habitat (Fig. 24.6). Contrast is used to define the amount of difference between two adjacent stands. For example, a very young deciduous stand in the initiation phase of stand development that is adjacent to an old-growth coniferous stand would have high contrast, but two adjacent stands that are of similar age and species composition would have low contrast. Juxtaposition is defined as the placement of two stands adjacent to each other.

The initial interest in edges was for game purposes, but it was subsequently discovered that many non-game species are also edge related. In some cases, there is an actual preference for the edge conditions rather than just

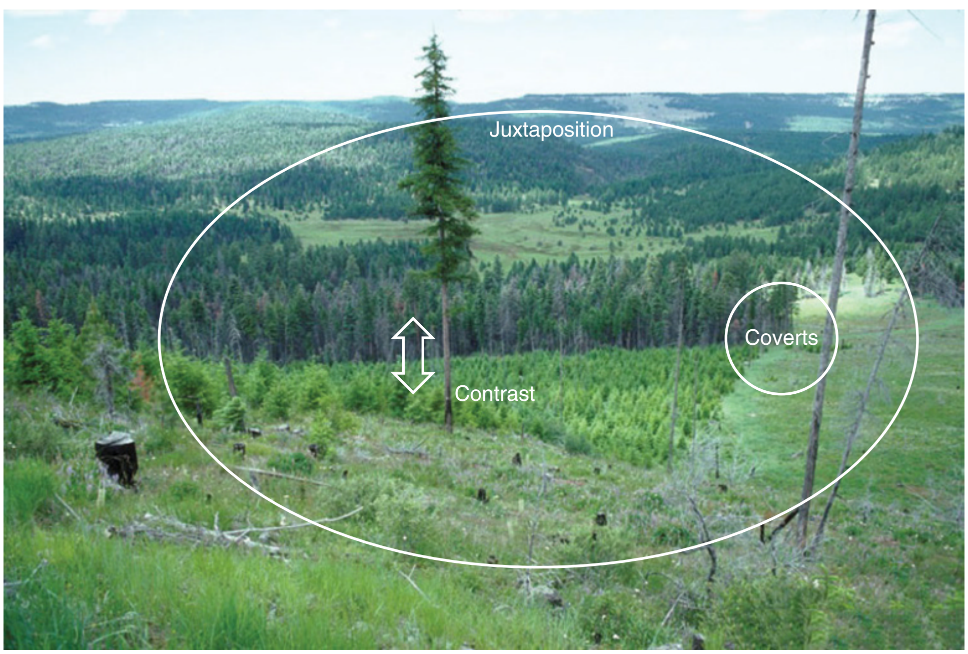


Figure 24.6 Image of stands depicting coverts, contrast, and juxtaposition, in the Umatilla National Forest, Oregon. *Source:* D. Powell, US Forest Service, Bugwood.org. Reproduced with permission from Bugwood.org.

a need for two or more habitats. Both microclimate and vegetation change along a sharp gradient at an edge, creating conditions different from those found in either habitat. At edges between mature stands and adjacent low vegetation of a very young stand, differences in wind speed, humidity, temperature, and solar radiation extend well into the interior of the mature forest stand. Forest edges also have a marked vertical structure from the forest canopy top to seedlings, shrubs, or grasses of the adjacent vegetation. The indigo bunting, a songbird that nests in the eastern US, is an example of a species that makes use of the edge itself; the female generally builds a nest in dense shrubs, but the male defends the territory from a perch in tall trees. Some plants also prosper along edges, including vines that are relatively intolerant of shade but require large trees for support. In general, the diversity of species in many taxa has been found to be greater in edge habitats than in continuous forest vegetation.

Edges occur naturally along the perimeters of forest destruction caused by wind or fire, and along abrupt transitions in site conditions. However, humans have added greatly to the prevalence of edges from agriculture and timber harvesting in many regions. Having recognized the importance of this habitat, wildlife biologists promoted the creation of edge as a basic goal of habitat management by prescribed burning and cutting. This was the principal rule of habitat management for several decades after its introduction by Leopold (1933). On forested areas where habitat management was the primary goal, artificial cutting patterns have been used to maximize edge, including harvesting in alternating strips or in checkerboard patterns. In areas where timber management was influenced by concern for wildlife, harvesting plans were modified by using a larger number of smaller cuts to achieve the desired harvest, by using stand shapes that were more oval than circular, by creating irregular edges, and by leaving islands of uncut trees within the cutting block. In addition, cutting areas were dispersed across the forest area to spread the influence of gaps across a larger area (Fig. 24.7). The fact that these edge-increasing modifications could be fairly easily incorporated into timber plans is another reason why timber management and habitat management have been regarded as compatible.

The Disadvantages of Maximizing Forest Edge

Although experience has shown that these practices are generally successful for benefitting edge species and increasing species diversity, wildlife biologists no longer believe that maximizing edge is a rule to be applied in all

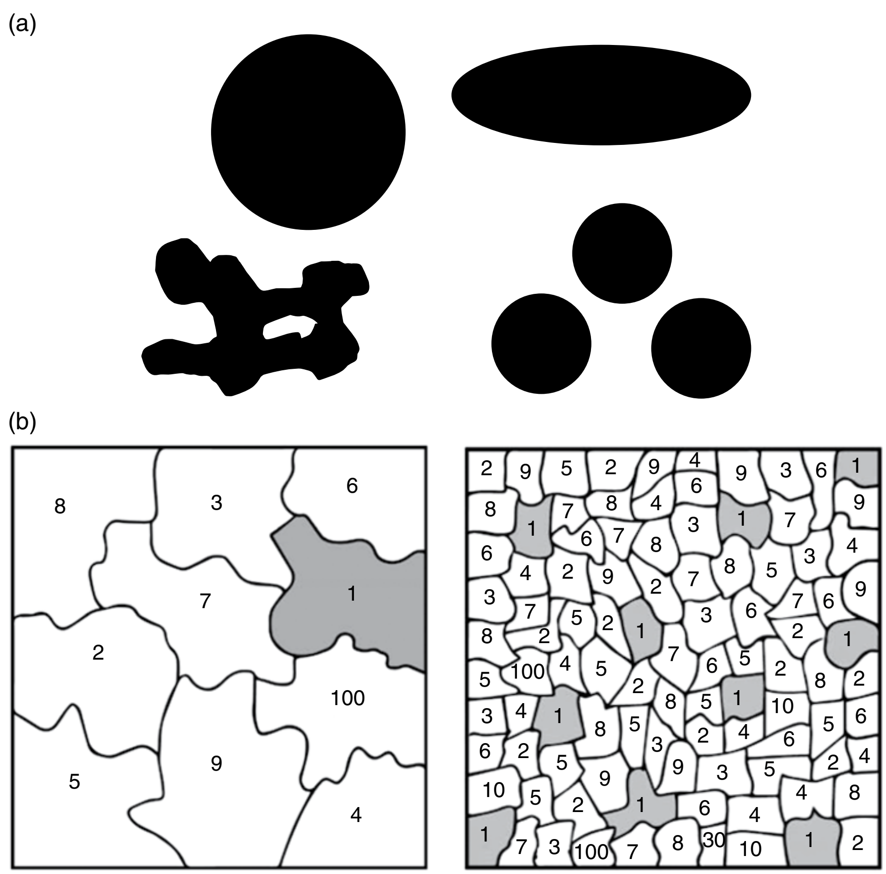


Figure 24.7 Modification of cutting patterns to increase the amount of edge for a given area harvested. **(a)** Stand level: circular cuts have the shortest edge length; the edge can be increased moderately by using elongated shapes, but much greater increases can be achieved by creating a cluster of smaller cuts, or making cuts with irregular edges that contain islands of residual trees. **(b)** Forest level: both drawings represent 1000-acre forests with balanced age-class distributions as indicated by the age shown for each stand. The youngest stands are shaded, indicating the areas where distinct edge habitat exists. The use of 10-acre stands rather than 100-acre stands disperses edge habitat throughout the forest area. *Source:* **(a, b)** Yale School of Forestry and Environmental Studies.

situations for all habitat purposes. The habitat requirements of interior species were not recognized earlier, partly because of the concentration on game animals, but also because of the stress placed on quantitative measures of overall diversity, which generally show increases when edge is created. However, increasing diversity at the local level may have an adverse impact on regional diversity. The problem is that when an edge-maximizing approach is used over a wide area, local diversity will in fact increase, but regional diversity may decline, as the same set of interior species is lost across the region (Murcia, 1995).

In forests where early-successional and edge habitat is to be promoted, careful consideration is needed. It is best to locate forests adjacent to properties and land uses where vegetation is already early successional, perhaps from the impacts of recent past land uses (e.g., old agricultural fields). If no young vegetation exists that can be promoted, then treating forest that is adjacent to farmland or forest fragmented with house lots can both complement and avoid impacting interior forest conditions elsewhere. This strategy certainly benefits early-successional generalists, such as deer (Alverson, Waller, and Solheim, 1988).

Some of the most serious declines of interior species populations have been identified in the midwestern US (Dijak and Thompson, 2000) and in parts of the tropics, particularly in Brazil (Woodroffe and Ginsberg, 1998), where forest land has undergone fragmentation and reduction in overall extent as a result of the development of agricultural and suburban lands. Conservationists in these areas have advocated the approach of retaining forests in the largest blocks possible in order to reduce further fragmentation (Woodroffe and Ginsberg, 1998). This is particularly the case for large mammals that have wide ranges (e.g., predators such as big cats). The attention given to these cases has led to the possibility that minimizing forest fragmentation may become a rule to be universally applied in habitat management, just as creating edge had been in the past. It is useful to consider the difference between these situations and that of harvesting stands in a predominantly forested region. The ideas of edge, stand size, and spatial arrangement that have been incorporated into the theoretical framework of landscape ecology (Forman and Godron, 1986) are helpful in this regard. The key concept is that a landscape is made up of a **matrix** (the predominant vegetation type) in which **patches** of other vegetation exist, which may or may not be connected by **corridors** of vegetation similar to that in the patches.

The situations in which fragmentation has had the most serious effects on interior species are those in which agricultural or suburban development has produced a non-forest landscape matrix, with forest being reduced to patches (Dijak and Thompson, 2000). In such circumstances, nest predation of forest-dwelling birds is much higher from agricultural-edge and urban-edge animals, such as raccoons and possums (Dijak and Thompson, 2000). Many forest-interior bird species avoid forests with these kinds of edges.

In contrast, harvesting trees generally produces grass/forb and shrub/seedling patches within a more mature forest. The same species that avoid forest edges that are adjacent to agricultural lands will use the forest close to the edge of an opening containing young stands regenerating after harvest (Hartley and Hunter, 1998; Flaspohler, Temple, and Rosenfield, 2001).

Other differences also exist between these situations, with an important one being the persistence of edge through time. Conversion of forests to agricultural fields or other uses, though not truly permanent, may last for centuries. In contrast, the goal of forest management is to produce regeneration that quickly develops into stands of large trees. Although it may take more than 100 years for these stands to reach the conditions needed for some interior species, many of the edge conditions disappear in a decade or two. Habitats may no longer exist for edge predators or parasites, and the vegetation may provide enough cover for interior species to travel across these areas to reach other mature forests (Flaspohler, Temple, and Rosenfield, 2001). For example, the brown-headed cowbird has been implicated as one of the major problems reducing forest-interior bird populations nesting in North America. Cowbirds feed mainly on seeds in grassy habitats, and lay eggs in the nests of other forest birds; the cowbird hatchlings then displace the young of the host species. This appears to be a problem mainly in forest fragments in agricultural and suburban areas, where cowbirds have abundant feeding habitat, rather than in continuously forested areas containing patches of young trees and shrubs. The important point is that the effects of edges created by forest fragmentation in some landscapes cannot be generalized to all situations (DeGraaf and Healy, 1990).

The situation in which cutting in forested areas is most similar to land conversion in its effects on forest-interior species, is that in which old-growth stands are harvested at a fairly rapid pace. In some forest types, the period before old-growth structure redevelops is so long that it can be considered a permanent change (at least on the same order of much agricultural land conversion). It is logical in such areas that the principle of minimizing fragmentation of the remaining old growth has been emphasized (Franklin and Forman, 1987), but this again is not necessarily equivalent to the effects of forest management on a sustained-yield basis.

In all forest management, however, the different needs of interior and edge species do create a clear conflict between the two rules dealing with stand size and spatial arrangement: "create more edge" and "avoid fragmentation"

(Hunter, 2010). In some cases, one or the other of these approaches may prevail, depending on the species of greatest concern. It may be possible to develop habitat for both kinds of species on the same area, if the management area is large enough. Patchy habitats providing edge could be restricted to one section, incorporating the ideas for maximizing edge, previously discussed. Other sections could be managed in larger homogeneous blocks, arranged in such a way that mature stands had the least edge possible with younger stands. General approaches of allocating land to different management strategies have been outlined by Harris (1984) and Noss (1983). These include a central core of old-growth reserve surrounded by areas of successively more patchy, heterogeneous forest, with increasing distance from the center.

An additional consideration is the appropriate stand size for habitat purposes. The realization that disturbances are a natural part of stand dynamics, has led to the idea that creating stands that mimic the size and severity of natural disturbances occurring in a region would be beneficial to the native species adapted to those forests (Bergeron *et al*., 1999; Long, 2009). The scale of disturbances ranges from large-scale stand-replacing hot fires to minor wind disturbances that create single-tree gaps. Although one kind may predominate in a region, most areas likely experience a range of disturbance effects. For example, large fires are the most apparent disturbance in the northern Rockies, but these are infrequent, with low-intensity fires occurring in intervening years. This combination produces even-aged stands of various sizes, as well as some with partial residual overstories (Amo, 1980; Long, 2009). This forest structure would be mimicked by a mixture of small and large clearcuts, incorporating heavy thinning or shelterwood cutting in some stands. In contrast, most New England forests are relatively free of large, stand-replacing fires. The death or windthrow of individual trees produces an old-growth structure at about 150 years old, but infrequent catastrophic windstorms destroy forests over large areas. Resulting stand structures range from a predominantly mature canopy with small gaps, to nearly complete destruction with only scattered residuals after major storm damage, to complete destruction when windstorm damage is followed by fire in the downed fuels (Foster, 1988). These structures could be mimicked by selection, irregular shelterwood, and clearcutting methods, respectively.

Not enough information is available for most regions to enable forest managers to precisely mimic natural disturbance processes, but it has been proposed as a general principle that silvicultural plans should incorporate a range of disturbance sizes across a landscape (Harris, 1984; Bergeron, *et al*., 1999; Niemela, 1999; Long, 2009; Hunter, 2010). The important idea is that natural processes tend to leave a greater range of stand sizes and structures than occurs when a limited set of silvicultural methods is applied across a landscape.

In these considerations, it is clear that some species are dependent on mature forests in which single-tree gaps are the prevalent disturbance size. The question then arises about the other end of the scale: to what extent are some species dependent on large areas of early-successional stands? Small raptors, such as the American kestrel, appear to have the need for the largest areas of herbaceous and seedling vegetation in order to hunt for small mammals; a minimum of about 100 acres (40 ha) may be needed to support this species (Hunter, 2010). Young stands of this size are also important for providing habitat for populations of some warbler species, even though a pair may survive on smaller areas. It is unlikely that species would require stands resulting from harvests in larger contiguous blocks. Many species with large ranges can use heterogeneous habitats.

Landscape Elements Across Stands

The stand-level attributes of wildlife habitat and the differences in age, structure, and composition of adjacent stands (i.e., the edge effect) have been described in the previous sections. The next part of the chapter is to consider the management planning and arrangement of stands across landscapes.

Sizes and Spatial Arrangement of Stands

There are limits to accomplishing habitat objectives by treating individual stands, and much depends on management at the forest level. Habitat elements tend to occur either in the earliest stages of stand development or in old forests (see Fig. 24.1). Herbage, browse, cover, and soft mast are in greatest abundance for most wildlife species during the stand-initiation stage. A diverse insect community, providing food for many higher animals, also exists in young stands, attracted to the flowers, fruits, and distinct microclimate of this stage. Cavities, dead wood, hard mast, and a different set of insect species (mainly wood decomposers) occur in mature forests. Intermediate stages have much less value for most species, but are of course a necessary step in the progress from young to old forest, in natural or managed forests. The most efficient way to provide a diversity of habitat structure is to maintain a distribution of stands of different ages across a forest landscape, such that all stages are represented at any time. This kind of age-class distribution is the goal of sustained-yield timber management (see Chapter 30).

It has been repeatedly suggested that "good forest management" (i.e., sustained-yield timber management) is automatically "good wildlife management."

The principal basis for this idea is the similarity in the need for a distribution of age classes. However, it is more accurate to say that the age-class balance of timber management can be taken as a starting point for the consideration of habitat management, with the question then being, what further factors or ideas should be considered for creating optimum habitat conditions? Some of these additional ideas include the overall master planning of the effects of forest tree-species composition, provision of old-growth habitat, sizes and spatial arrangement of stands, locations of corridors, and the landscape context of the management area.

Reserve Design for the Forest Interior

It has been discovered that some species predictably decline in abundance when early-successional habitat is created. These species require a minimum area of a single habitat and are referred to as **interior** species. There are several potential reasons for the decline of forest-interior species in patchy forests with plentiful edges: predators and parasites that live in non-forest habitats along edges may move into the stand to prey on forest species, edge-adapted species may be better competitors in the conditions near edges, or the remaining forest habitat simply may not be large enough to support the minimum social group of a species.

The best-known examples of interior species may be those such as the northern spotted owl that inhabit old-growth stands, but they are not the only ones. The large group of songbird species known as neotropical migrants, which breed in North America but overwinter in Central and South America, have been the focus of considerable attention, although some of these species are edge inhabitants, such as the previously mentioned indigo bunting. Others are forest-interior species, and still others are shrubland- or grassland-interior species. Habitat management for these interior species requires the opposite of that for edge species; each vegetation age class should be created in the largest possible blocks with smooth edges.

There are certain shapes and sizes of stands that minimize edge and maximize interior habitat in reserve design (Fig. 24.8). The best reserves that minimize edge are large and circular. The worst shapes for interior are long and narrow. Designing reserves and arranging stands to maximize forest interior habitat is considered critical in forests and regions where it is important to minimize fragmentation. This is all dependent upon the surrounding land-use context of the forest to be managed. If the forest area to be managed is the only intact block surrounded by suburbanization or farmland, the development of a reserve system and a set of silvicultural treatments that minimizes the creation of early-successional habitat is critical. If the forest to be managed is embedded within an extensive area of intact mature forest then the development of a large protected interior reserve is perhaps not so critical.

To design an interior reserve system within a managed forest, it is best to use the underlying physiographic and hydrological template of the forest itself as a guide (see Chapter 3 on defining the scale of stand size). Ultimately, the shape and scale of a forest is constrained by physiography and the nature of topographic relief. From this, the

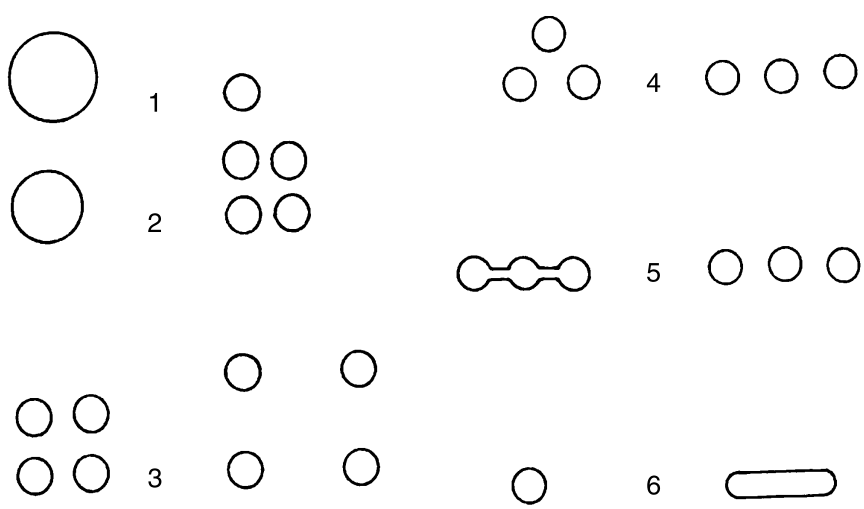


Figure 24.8 Shapes and sizes in reserve design: prioritizing interior old-growth or late-successional reserve shapes and arrangements within managed forests. 1. Large patch or circular areas are the best shape because they have maximum interior and minimum edge influences. 2. It is better to maintain the biggest patches available rather than to have four smaller patches close to each other. 3. It is best to site reserve patches as close to each other as possible, rather than to have them arranged further apart. 4. Reserves arranged for maximum interaction together are better than those that are arranged linearly or that minimize interactions to only one or two directions. 5. Those reserves that are arranged linearly are best connected by a reserve corridor. 6. Corridors that are shaped to minimize edge are better than those that maximize edge. *Source:* Adapted from Hunter, 1999.

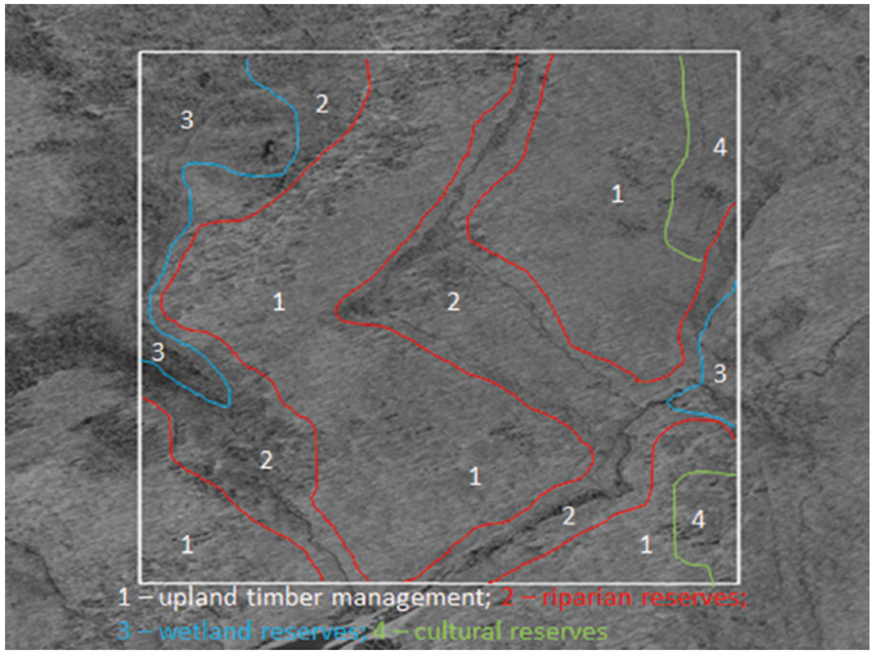


Figure 24.9 An example of stands allocated to a reserve design using the protocols outlined in Fig. 24.8. *Source:* Mark S. Ashton.

most useful first start is identifying and mapping all water bodies and sensitive soils (wetlands, seeps, soils prone to erosion or landslides). The way water is retained and runs off the landscape will help define the scale of reserve design in size and shape. The second step is to identify and map unique ecological areas based on forest composition, age, structure, and soil. Old-growth or potential old-growth forests would be included in this category. The third step is to identify and map several large contiguous areas that comprise stands that envelop these core features of water, wetland, and ecological landscape features mentioned in steps one and two. The fourth and last is to identify and map smaller stands with current or future old-growth potential as secondary nodes that can be connected to the reserve network through riparia (Fig. 24.9).

The last thing to consider when practicing even-aged management is the temporal and spatial arrangement of management operations around the reserve areas. In general, to minimize impact of even-aged management on interior-reserve habitat, it is best to purposely operate and treat stands in one area together at the same time or over a short period of time relative to the length of time a stand takes to develop to maturity, and then move to another area. In this way, management is minimizing the fragmentation of an area both in time and space. For example, it is better to regenerate all stands in an area of the forest together than regenerating stands adjacent to each other at different times. The former provides much greater structural homogeneity than the latter (Fig. 24.10). However, if practicing all-aged regeneration with selection methods, the limiting concern is ensuring that gap size is not large enough to dramatically alter the species composition and structure of the original mature forest. Smaller gaps are therefore desired over larger ones. This will undoubtedly change species composition but for many species of wildlife this may not be of important concern as compared to ensuring the right vertical structure.

The Design of Reserves and Connectivity for Interior Species within Managed Forest

In situations where patchy forest structure has been created, corridors of vegetation that connect patches of similar vegetation structure can help to minimize the negative effects on some wildlife species. They may be important at very different scales. In a regional context, maintaining forest vegetation in corridors that connect forest areas in an agricultural landscape allows the migration of plant and animal species over various time scales: daily, annual, or many generations. These large corridors are beyond the scale of silvicultural planning; their most important attribute is that they remain forested in some form, rather than any particular management scheme that would be carried out within them. Such corridors are not considered beneficial in all cases; they can sometimes cause problems if they serve as a conduit for exotic species or diseases into previously unaffected areas. They can also serve as barriers to some wildlife and facilitate movement for others. For example, hedgerows and living fences are very important conduits for moving from one woodland to another for small mammals and birds, but are obviously barriers to livestock.

Corridors connecting individual stands within a managed forest are of more importance in silviculture. The most important kind of corridor is often referred

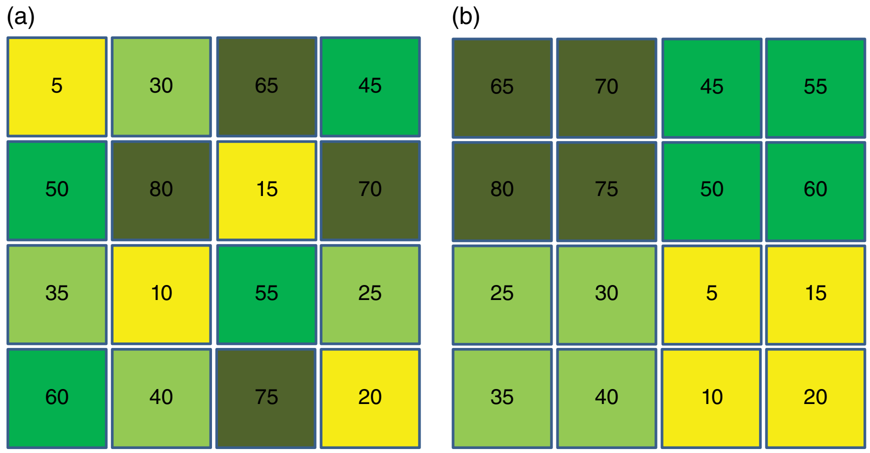


Figure 24.10 A graphical depiction of two different spatial and temporal kinds of operations to manage a forest for greater or lesser structural and spatial heterogeneity. In this example, stands are depicted as squares and the numbers define their age. The colors denote stage of stand development: yellow – stand initiation; pale green – early stem exclusion; emerald green – late stem exclusion; and dark green – understory initiation/mature. The group of 16 stands on the left **(a)** illustrates regeneration treatments for each stand that are planned separately and conducted at different times, creating a more heterogeneous mix of age classes and structures across stands but one that is more homogeneous across the whole forest. The group of 16 stands on the right **(b)** illustrates regeneration treatments for each stand that are planned in the same area together, creating greater across-stand homogeneity of age classes and structure across a landscape, but a more disparate arrangement of age classes and structure across the whole forest area. *Source:* **(a, b)** Adapted from Hunter, 2010.

to as a **leave strip**: a strip of uncut or partially cut forest crossing through a harvested area. When cutting blocks are larger than about 100 acres (40 ha), the ability of wildlife to move between stands begins to be inhibited because of lack of cover, especially immediately after cutting. Leave strips are useful as long as they are wide enough to provide escape cover. A width of only 20 ft (6 m) is useful to some small animals, but corridors 10 times that width or more may be required for deer and elk. These larger widths are also needed if the objective is to provide food or other habitat elements within the corridor, rather than just escape cover for movement.

Riparian zones serve as the most logical locations for leave strips. These are already preferred habitats and form a natural network connecting various parts of the landscape. This use also is compatible with the need for filter strips around water bodies. Riparian leave strips have the greatest importance when large harvested areas are converted to plantations of simple structure with little habitat value, and they serve to mitigate habitat effects that last through the rotation.

Corridors serving the reverse purpose of leave strips (harvested corridors connecting areas of early succession) are generally not necessary and may be detrimental by creating edge through mature stands. Most animal species using patches of open habitat will travel through older forest. Young vegetation corridors of limited length are sometimes valuable to connect small clearcuts within a cluster; sowing seed of herbaceous species on logging trails can generally provide for this when needed.

Regeneration Methods in Model Landscapes

Even-aged methods of regeneration create strong homogeneity in structure and species composition within a stand, but much greater temporal variation with change in developmental phase as compared to uneven-aged (all-aged) methods. Irregular two-aged or three-aged systems (multiple-aged) are somewhere in between. Species composition and degree of vertical stratification also changes with regeneration method. As would be expected in even-aged methods, the simplest structures and species mixtures arise from true clearcuts and coppice systems, and greatest diversity of species mixtures and structural stratification originates from shelterwoods. Also, clearcuts and coppice systems may not change in species composition or structure nearly as much as shelterwoods. All-aged selection methods obviously create the greatest structural and compositional spatial heterogeneity but should remain the same over time (Table 24.4). In a study for an oak–hardwood–conifer forest in southern New England, breeding bird abundance and diversity was highest in regenerating shelterwoods as compared to second-growth forest of about 100 years old that had either received crown thinnings or was unmanaged reserves. Each stand condition also reflected differences in bird composition with ground-nesting birds and woodpeckers having higher affinities for crown-thinned stands, canopy-nesting warblers having an affinity for stands that were unmanaged, and early seral warblers, sparrows, and finches having the greatest affinity to shelterwoods (Goodale *et al.*, 2009). These results appear to corroborate other studies in oak–hardwood stands of the midwest (Annand and Thompson, 1997) and southern

Table 24.4 The degree of temporal and spatial tree-species diversity by regeneration method.

	Temporal diversity in forest composition and structure	Spatial heterogeneity in composition and structure within stands	Spatial heterogeneity in composition and structure across stands
Rotations			
Coppice	2, C	3, C	2, B
Clearcut	1, C	3, C	1, B
Seed-tree	1, B	2, B	1, B
Shelterwood	1, A	2, B	1, A
Irregular seed-tree shelterwoods	1, A	1, A	2, A
Cutting cycles			
Selection	3, C	1, A	3, B

Structure: 1 – high, 2 – intermediate, 3 – low
Species composition: A – high, B – intermediate, C – low
Source: Mark S. Ashton.

Appalachians (Augenfeld, Franklin, and Synder, 2008; Newell and Rodewald, 2012).

Comparing levels of heterogeneity and homogeneity across stands at the landscape scale, even-aged methods are much more heterogeneous than uneven-aged methods, both in terms of species diversity and structure. This is particularly true when stands of different age are arranged adjacent to one another. When arranged into groups of similar age class, this can dramatically increase landscape-scale homogeneity. The greatest landscape-scale heterogeneity can be created by arranging stands of different age classes and regeneration methods adjacent to each other. Studies on breeding birds in northern hardwoods of New England and bottomland hardwood in the south have demonstrated that, at landscape scales, a mixture of methods is better than only one (King and DeGraaf, 2000; Moorman and Guynn, 2001; Doyon, Gagnon, and Giroux, 2005). Clearcutting in interior boreal forest provided greater breeding bird abundance and diversity than mature forest, but leaving snags and live reserve trees increased diversity further (Hobson and Schieck, 1999). However, for interior montane forest of the Pacific Northwest, greater homogeneity and older forest structures promoted the highest breeding bird diversities and abundance (Beese and Bryant, 1999).

The Landscape Context of a Management Area

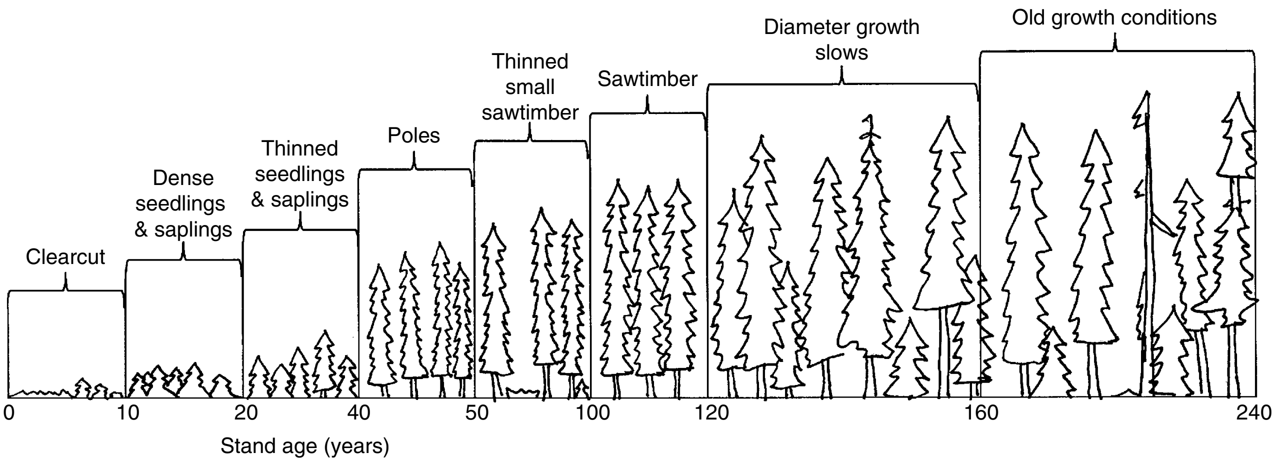
The success of many habitat-management efforts depends on the forest conditions that lie beyond the boundaries of a particular forest owner. It may not be possible to create sufficient habitat for some species on an ownership of limited size, if treatments produce only a small island in a regional landscape of unsuitable vegetation. Thus, decisions about management objectives must consider the landscape and the ability of managers to affect forest conditions on large areas. This need is clearly of greatest importance when the objective is to maintain regional biodiversity.

The goal of such efforts is to create a diversity of stand sizes, ages, and structures across a landscape, as previously discussed. However, it is common for roughly synchronous waves of human activities (heavy timber cutting or abandonment of farmlands) to create a predominance of one forest age class across large areas. In considering the management of a relatively small ownership, often the best that can be accomplished is to provide habitats that are rare on the landscape as a whole. A more comprehensive design of landscape vegetation becomes possible even where a large number of owners is involved, if incentives, regulations, and cooperative enterprises among owners are developed (Oliver, 1992).

Examples of Application

Elk and Woodpecker Habitat in Eastern Oregon

Management of game species that require edge habitat has long been integrated with timber management, but concern for non-game species that inhabit forest interiors is being increasingly incorporated on the same lands. One example of this balancing effort, described by Thomas (1979), deals with timber production and habitat management for elk and pileated woodpeckers in the Blue Mountains in northeastern Oregon, in forests dominated by ponderosa pine, Douglas-fir, and grand fir. Elk require three kinds of habitat: forage areas, escape cover, and thermal cover. The elk habitat conditions



Forage area	Escape cover		Thermal cover	Forage area	Thermal cover	Marginal habitat	Optimum habitat
Elk habitat						Woodpecker habitat	

Figure 24.11 Diagram of habitat conditions in managed mixed conifer stands in eastern Oregon, where extended rotations are used to provide old-growth stand structures. Elk habitat is provided in a 120-year rotation on 75% of the forest area, and pileated woodpecker habitat is provided on 25% of the area. *Source:* Yale School of Forestry and Environmental Studies.

provided at each stage of stand development are shown in Fig. 24.11, for a stand managed for sawtimber on a rotation of 120 years. Herbage and browse are produced during the first 10 years following cutting. Dense seedling and sapling stands form escape cover that lasts from 10–20 years, ending with the reduction in stand density from precommercial thinning. Thermal cover develops at age 40 as the canopy closes and increases in height, and it persists as long as the canopy exceeds 70% closure. Beyond that age, the stand shifts between providing foraging habitat and thermal cover as the stand is thinned and then the canopy recloses.

The key to habitat management for elk is to provide each of these three habitats in appropriate proportions and spatial arrangement. Both kinds of cover must occur within a short distance from forage areas; the appropriate scale to achieve this is at a stand size of about 25 acres (10 ha). These needs can be accommodated in a wide range of rotation lengths. If rotations are less than 50 years, thermal cover will not develop; if rotations extend beyond 140 years, the level of cutting becomes so low that early-successional forage and escape cover become scarce. However, the range of 50–140 years includes all the rotations likely to be used for timber production, and demonstrates the general compatibility of habitat management for edge species and timber management.

Pileated woodpeckers use considerably different habitats. They are large birds that excavate nest cavities in trees that are at least 20 in (50 cm) DBH. Their principal food consists of carpenter ants that inhabit trees or logs infected with heart rot. Stands develop trees suitable for nesting and feeding at an age of about 160 years. The territorial requirement for a pair of woodpeckers in this region is approximately 300 acres (120 ha) of mature forest. One approach for providing woodpecker habitat is to extend the rotation on approximately 25% of the forest to 240 years. These stands would have an old-growth structure for one-third of that rotation, which would give nearly 10% of the total forest as old-growth at any time, once a balanced age-class structure was achieved. These stands are best if they occur in large contiguous blocks; no special arrangement of stands is needed because woodpeckers do not need younger stands.

This approach would require modifications in management of the remaining 75% of the forest to maintain optimum conditions for elk, because of the overall reduction in harvest resulting from lengthening the rotation on 25% of the land. These modifications would include using prescribed fire or other means to delay regeneration on a portion of the harvested areas in order to maintain browse and herbage for an extended period, and altering the timing and intensity of precommercial thinning to lengthen the time that sapling/pole stands serve as escape cover (Smith and Long, 1987). This is only one possibility for balancing these habitats; other approaches include using old-growth reserves for woodpecker habitat, or maintaining mature reserve trees after harvest to shorten the time before managed stands provide suitable old-growth conditions.

Habitat Diversity in Southern New England

A second example illustrates a situation in which the objective is the conservation of all native species in a region. The setting of this example is the rolling terrain of the Berkshire Mountains in western Massachusetts, where northern hardwoods (beech, sugar maple, and yellow birch) predominate, and northern red oak occurs only on warmer south-facing slopes, being at the northern extent of its range. Most of the land in the region was cleared for pasture and cropland in the 18th and 19th centuries, but was later abandoned. Nearly all of the white pine stands that had invaded the abandoned fields were harvested, and forests are presently made up of mature hardwood stands that developed following the cutting. Only small stands of old-field pine remain. Most of the landscape is forested and is owned in small private woodlots, where only partial cutting is used. Harvests range from selection cutting to improvement thinning to high-grading, but they rarely remove a major part of the overstory canopy.

Management objectives on some of the lands in state ownership in this region are to create conditions favorable to overall species diversity. An analysis was conducted of the habitat requirements of all species of mammals, birds, amphibians, and reptiles that are native to the region (deGraaf *et al.*, 1992; Costello *et al.*, 2000; King and deGraaf, 2000), and a goal was set for the appropriate balance of forest age classes to meet those requirements. The habitat that is most critically in short supply on the landscape are the grass/forb and seedling/shrub stages, both in small patches for edge species and in larger blocks for interior species that require extensive areas of the late-successional habitat (Fig. 24.12).

The following description represents the general silvicultural plans for one state management area of approximately 1000 acres (400 ha) in this landscape. Treatments are limited to those for which costs can be covered by harvesting revenues. Specific treatments include the following.

1) Creating clusters of three to five patch openings, separated by strips of mature trees 50–100 ft (15–30 m) wide, where each cut is about 5 acres (2 ha), for a total area of 25 acres (10 ha). Some of these are converted to permanent openings by burning at 3-year intervals to maintain vegetation in a mix of herbaceous and woody species; others are left to develop into sapling stands as one-cut shelterwoods.
2) Producing a larger block of seedling/shrub habitat by regenerating stands of about 50 acres (20 ha). Mature stands containing red oak in the overstory are chosen in order to regenerate this most important mast species. Shelterwood cutting is used in these stands to establish oak advance regeneration; mature oaks are retained in the shelterwood overstory for mast

Figure 24.12 Edge habitat between early initiation and early stem-exclusion stands provide unique foraging and nesting habitat for early-successional birds of the southern New England forest. A higher abundance and diversity of breeding birds are found in this kind of early seral habitat than in interior forest. *Source:* Mark S. Ashton.

production and as seed sources. The dense understory of beech, which dominates after harvesting in northern hardwood stands, is cut back, and their stump surfaces are treated with herbicide to prevent resprouting; this promotes the development of a high diversity of early-successional plant species.

3) Regenerating the few remaining white pine stands in order to maintain as much conifer winter cover as possible. This is accomplished by shelterwood cutting coupled with scarification and control of the understory hardwoods. Several removal cuttings are used to slowly release the advance-regeneration pine in order to maintain the thermal cover value while assuring long-term dominance of pine on the site.
4) Developing vertical structure in some areas of mature forest by using selection cutting with small groups. This is of only secondary importance, compared to creation of stands of young vegetation. Other areas of mature forest are to be left untreated.

This management plan is an example of a relatively new approach to active modification of landscapes in order to create the appropriate habitat diversity for all native wildlife species (Costello *et al.*, 2000).

Biodiversity Conservation in Boreal Forests

A final example of the application of habitat management principles is one in which concerns for biodiversity are combined with large-scale industrial timber management in boreal forests. Much of the boreal region of the world is well suited to timber production because it contains vast conifer-dominated forests with few human inhabitants. Harsh climatic conditions cause natural levels of plant and animal diversity to be lower in forests than in most other regions. Stands are dominated by one or a few tree species consisting mainly of pine, spruce, fir, or larch. Hardwoods such as birch, willow, and poplar occur mainly in early-successional stages or in riparian areas. Forest industry has developed on a large scale in the countries of the boreal region, supplying the rest of the world with a substantial part of its industrial softwood.

As with other regions, timber harvesting in these forests was initially of an exploitative nature, but it was replaced by efforts to develop a sustainable timber economy. Many differences exist across this huge region, but a common pattern in management is discernable. Silvicultural innovations have concentrated on the tasks of assuring prompt regeneration of conifers and mechanizing operations for economic efficiency. Silvicultural treatments often consist of a sequence of clearcutting and planting. This means that the slash is burned, the site is mechanically prepared, and then planted with improved seedlings of a single species. Hardwood competition is removed in young plantations. These techniques have been successful where they have been applied, but the result is the creation of ecosystems that are even simpler than those that existed prior to treatment.

This simplification is most evident with the higher plants, and the bird and mammal communities that depend on them, but much of the natural diversity of these ecosystems occurs in the insect and fungi communities, which are also affected. Many of those species are dependent on dead wood, particularly that of hardwoods because of the higher nutrient content, and wood of deciduous species, living or dead, is in very short supply in intensively managed conifer stands.

Methods used to counteract these simplifying effects of silviculture have concentrated on saving mature living trees, snags, logs, and other important habitat elements during final harvesting (Fig. 24.13). These can be maintained during the process of conventional plantation establishment, but in some situations, a greater diversity in regeneration is also sought by altering the planting and site-preparation techniques. One form of this approach is to plant a conifer species at only about half the usual planting density, with site preparation being limited to those planting spots. This assures a minimum conifer crop on the site, which is supplemented by natural regeneration of both hardwood and conifer species that are allowed to develop between the planted trees. At a larger scale, extensive reserves designed around water bodies, wetlands, remaining old growth, and ecologically novel habitats can create a more diverse array of composition and structure suited to interior wildlife species and habitat specialists (Bergeron *et al.*, 2001).

Although it may be possible to use the selection system for conservation of some habitat elements, past attempts at selection cutting in boreal forests have frequently resulted in poor regeneration (Hagner, 1995). The use of mixed-species natural regeneration, prescribed fire, and the retention of snags, logs, and reserve trees in even-aged stands may be more suitable for habitat conservation, because the natural stand-development processes in these forests are initiated by large hot fires (Nilsson and Wardle, 2005).

Creating Red-Cockaded Woodpecker Habitat in Southern Pine Forests

Red-cockaded woodpeckers are colonial breeders that require pine forests in the southern US. One breeding pair usually has several sub-adults from prior nesting as helpers. The woodpeckers create cavities in pine trees in about 2 years if the trees are loblolly or shortleaf pine, but up to 6 years if they are longleaf pine. The birds select the largest and oldest trees in the pine stand and, in particular, those trees that are infected with red-heart fungus (Conner *et al.*, 1996). The cavity trees selected by woodpeckers are at least 85–130 years of age (Rudolph and

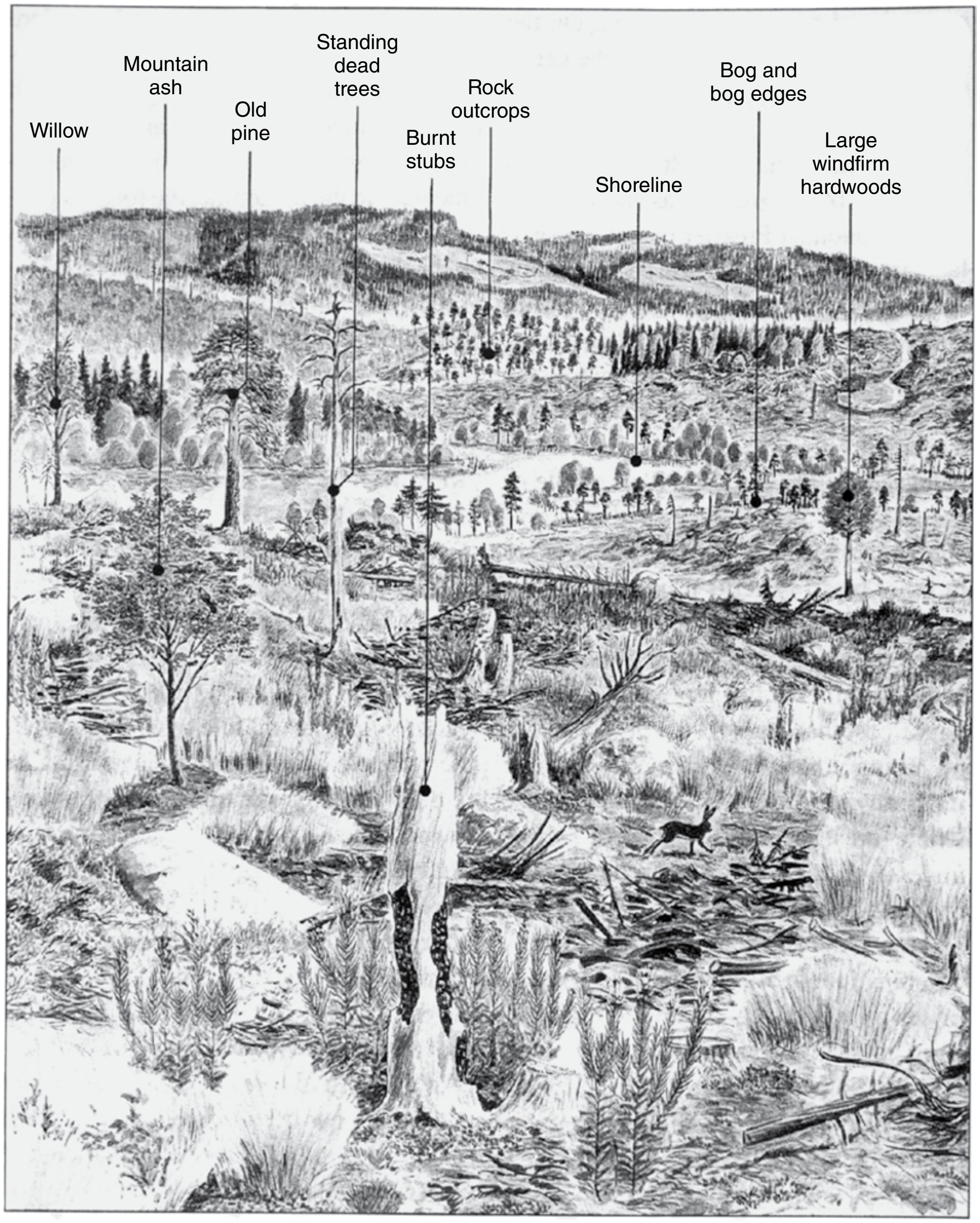


Figure 24.13 Diagram from a Swedish silviculture manual indicating important habitat elements to be retained during final harvest of conifer-dominated stands in boreal forests. *Source:* Hagner, 1995.

Conner, 1991) with a preference for trees greater than 30 in (76 cm) DBH (Engstrom and Sanders, 1997).

On productive sites such as old-growth longleaf pine stands, woodpecker group sizes can be up to seven individuals. Productive sites comprise numerous older and larger trees for foraging, thus making their territories year-round amount to no more than 50 acres (20 ha), as compared to sites with poor age classes and structures where territories can be greater than 100 acres (40 ha) (Engstrom and Sanders, 1997). Woodpeckers have a complete intolerance of hardwood mid-story trees near cavity pines, though a hardwood component elsewhere in the stand is acceptable (Fig. 24.14). In addition, flying squirrels, once thought to directly compete for woodpecker cavities, can actually co-habit stands, occupying cavities in adjacent trees (Conner *et al.*, 1996). Diets of red-cockaded woodpecker comprise a high proportion of ants and their eggs, and larvae that reside in the pine wood.

To manage for red-cockaded woodpecker habitat, pine forests that are overstocked and that have hardwood understories need to be thinned in the canopy and most

(a) (b)

Figure 24.14 **(a)** Marking a red-cockaded woodpecker cavity tree for retention and protection before applying a prescribed burn to reduce the understory. **(b)** An example of a nest box that will be inserted into a pine tree to attract woodpeckers. *Source:* **(a, b)** Mark S. Ashton.

of the mid-story removed, particularly around those trees that are older and larger. The reintroduction of fire can maintain this kind of structure, encouraging a grass and brush understory and preventing the release of more hardwood regrowth into the mid-story. Studies show that apart from red-cockaded woodpecker habitat, the new habitat creates increases in the breeding and winter resident bird diversity and abundance, and dramatically increases habitat for another rare and endangered species, the Bachman's sparrow (Wilson, Masters, and Bukenhofer, 1995; Conner *et al*., 2002)

Control of Wildlife Damage to Trees

This chapter has been devoted to ideas about manipulating forest vegetation to maintain or increase wildlife populations, but sometimes such populations become so large that they cause serious damage to stands (Horsley, Stout, and DeCalesta, 2003). The most widespread problem results from deer and elk browsing on seedlings, but there are also situations in which small mammals damage seedlings by girdling them as they feed on the bark. Part of the solution involves favoring species such as spruce that are not palatable to browsing animals, as well as regulating the habitat of the animals to make it less favorable to them (Black, 1992).

Damage by deer and elk has long been such a serious impediment to regeneration in Europe, Australia, and New Zealand that foresters have resorted to fencing regeneration areas or using plastic tree shelters placed around individual seedlings. Chemical repellents are also used to spare seedlings from browsing. Such damage is of increasing concern in North America, and if other ways are not devised to control these animals, these expensive remedies may become more common here. Plantings are particularly susceptible to browse damage when adjacent to existing forest cover, because, as noted in prior sections, this promotes a "settling stimulus" for herbivores.

Another part of the solution is to recognize that large herbivores can become as much of a pest of the forests as are fires, root decay fungi, or defoliating insects. To meet objectives, the animal population of the forest must be managed just like that of the plants. In fact, one cannot be managed without also managing the other. Hunting is an important tool of wildlife management for the same reason that cutting is in silviculture, each can be used as a means of mimicking natural processes that occur in forest ecosystems in order to meet human objectives.

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25

Silvicultural Applications to Forest Restoration: Rehabilitation and Reclamation

Introduction

Measures and strategies for reforesting, rehabilitating, and reclaiming lands that were former forest lands and that are now wastelands, are vital parts of any silvicultural system. Ensuring forest restoration is so important that it is usually dealt with in separate advanced academic courses (Falk, Palmer, and Zedler, 2006; Ashton *et al.*, 2014a; Stanturf, Palik, and Dumroese, 2014). This chapter deals only with examples of modifications of silvicultural systems that are designed to: (1) rehabilitate forests after overexploitation or land conversion and degradation from inappropriate and over-use; and (2) reclaim severely degraded lands that require substantial human inputs in changing soils and hydrology to create conditions for new forests to grow. Examples of lands that require rehabilitation include repeatedly logged-over forests using diameter-limit operations, overexploitation of non-timber forest products, and conversion of forest land to agriculture and ranching lands that are managed in a way that cannot maintain long-term site productivity. Examples where unstable lands need to be reclaimed back to various forms of forest for increased stability varies from lands whose sub-surface soils and geologies have been strip mined, where catastrophic floods have transformed landscapes to deposits of silts and sands, or where urban waste has created mountains of land fill. The suggested treatments and modifications are mostly steps taken against specific forest degradation phenomena and damaging agencies and cannot be safely based on generalities applicable to all forests. Appropriate procedures must therefore be based on the details of knowledge about the sources of damage and degradation.

The chapter can be divided into several parts starting with an introduction defining the different kinds of degradation and restoration processes of land and forests, and then categorizing the different levels of degradation and restoration into three levels of severity: (1) low-severity degradation and forest rehabilitation; (2) medium-severity degradation; and (3) forest rehabilitation and severe degradation and land reclamation.

Degradation and Restoration Processes of Forests

Forest restoration is now a global issue with over 5 billion acres (2 billion hectares) of forests in some form of degraded state, underperforming in ecological productivity and integrity, or in the ability to deliver the multiple social and economic demands of society. Stanturf, Palik, and Dumroese (2014) state that when restoration is defined as a practice it is really borrowing techniques from silviculture. There is no real distinction between restoration practice and silviculture other than the fact that the techniques used in restoration are usually practiced under extraordinary circumstances of ecosystem degradation. Like the practice of silviculture, restoration is guided and driven by social and economic values with the objective that the the sum of these values can be improved or increased. **Restoration** as a term can also be used narrowly as a literal interpretation of "restoring" to an original baseline condition, or it can be defined more broadly to include more refined words such as rehabilitation and reclamation (Fig. 25.1). **Rehabilitation** restores ecological processes, species composition, and structure on the same trajectory as restoration (narrowly defined) but at a lower level as compared to the original ecosystem. **Reclamation** restores soil and site productivity with new and novel assemblages of plants on severely degraded sites that have no original vegetation cover remaining.

Concept of Forest Degradation

Degradation can affect forests to varying degrees from the complete removal of the vegetation and the mineral topsoil in one impact (e.g., surface mining) to the ever-present impacts of air pollutants on the forest canopy affecting species composition and growth. For restoration purposes it is best to define different levels of silvicultural input depending upon the degree of degradation (Fig. 25.1). Degradation can be categorized as either **vegetative** or **physiochemical**. Vegetative aspects of degradation affect the the forest structure, composition,

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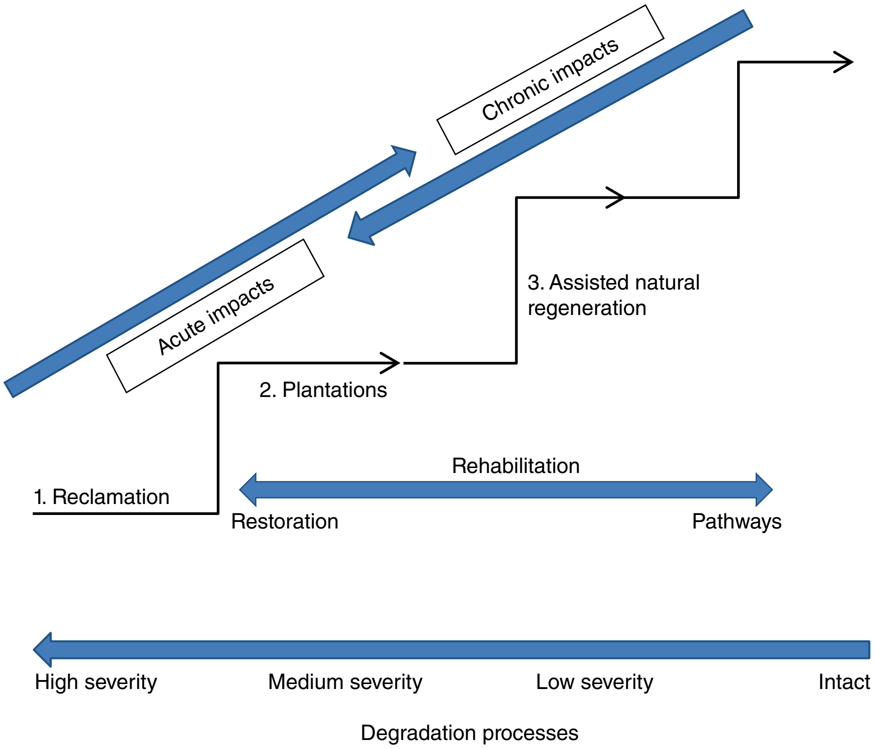


Figure 25.1 The restoration staircase. Depending on the state of land degradation of an initially forested ecosystem, a range of silvicultural approaches can be undertaken depending upon degree of degradation. The diagram provides a conceptual understanding of the relationships between the severity of degradation and the incremental degree of restoration associated with the level of degradation. The most severe degree of degradation is associated with acute disturbance impacts (e.g., strip mining) that dramatically alter the hydrology and soil. The restoration approach would be 1: land reclamation. Medium-severity degradation is usually associated with acute disturbance impacts (e.g., forest clearance for pasture) that eliminates the structure and composition of the original vegetation. The restoration approach would be 2: rehabilitation through planting or natural regeneration. Low-severity degradation is mostly a chronic disturbance impact (selective logging, air pollution) that slowly reduces the original vegetative structure and composition of the forest. The restoration approach would be 3: rehabilitation through rest and enrichment planting. *Source:* Adapted from Chazdon, 2008.

and development. Vegetative degradation encompasses those impacts that alter tree-species composition and stature in a way that moves the forest condition to a state that does not easily move back to the original condition. Examples are numerous, including: conditions where fire has been excluded, over-grazing, selective logging, and forest clearance and transformation to grassland and agriculture. Rehabilitation techniques are chiefly associated with vegetative degradation.

Physiochemical aspects of degradation affect the integrity of the soil fertility and hydrology. The more severe form of degradation is the physiochemical, given that the actual soil resource is affected changing fertility and hydrology and, by implication, site productivity, rather than vegetative which affects the tree-species composition and its structure (e.g., height, age-class and diameter distribution). Reclamation techniques are chiefly associated with physiochemical degradation. The two types of degradation are often strongly interrelated and managers must often address several forms of degradation simultaneously.

There is substantial evidence to show that forest conversion to permanent agriculture is the primary physiochemical degradation factor that can affect site productivity. Conversion of forestland to agriculture is almost a general phenomenon in the world, but much of this land is marginal at best. It is susceptible to soil erosion, nutrient loss, and structural changes that change the hydrology and water-holding capacity. Many of these forests are on highly weathered, nutrient-poor soils on ancient geologies, or on steep slopes and unstable geologies. Agriculture itself can be a source of degradation from use of inappropriate irrigation or drainage that can lead to substrate salinization and subsidence, respectively. More severe kinds of physiochemical degradation include surface mining, landfills, and urban wastelands, although all are found in more localized areas than agricultural lands.

Other kinds of physiochemical degradation are often innocuous and difficult to detect because of their ongoing nature. One example is climate change and its multiple interacting stressors, in which more pronounced variations in precipitation and temperature interact to accentuate droughts, heat waves, cold spells, and precipitation events. In turn, this changes the soil's physical and chemical properties and weathering processes.

These effects all interact to alter the organismal component, namely species composition and structure of a forest. A more localized or regional problem can be air pollution. Historically it was "acid rain," mainly from the sulfur dioxide being emitted from power plants, that caused changes. This has largely been mitigated by the US Environmental Protection Agency (EPA) mandates. However, nitrogen deposition from the nitrogen dioxide of car exhausts, ozone damage, and heavy metals (especially mercury) from powerplants pose other ongoing physiochemical threats to forest productivity and growth (see Chapter 26 for forest health).

Physiochemical degradation by pollutants and changes in climate can also be categorized as vegetative when it alters forest composition and structure, and changes composition of soil microbiota. However, more obvious forms of vegetative degradation are the direct impacts related to overexploitation of a resource whether it be for **forage**, **forest products** (timber and non-timber forest plant species), or **hunting** (e.g., elimination of tree seed-dispersal agents). All three exploitation factors are main causes of forest degradation that are often within the control of the forester, if strong environmental laws and enforcement exist. All three factors can dramatically eradicate species of plants or animals from the forest ecosystem. Examples of overgrazing exist in many forest regions where livestock have been left to roam freely without careful control of timing and numbers [e.g., in the US southwest in the 19th century (Covington and Moore, 1994), or presently in the Chaco of Argentina (Abril and Butcher, 2001)]. Eradicating species of timber through commercial exploitation is a common phenomenon for precious woods, such as the mahoganies and rosewood. Such activities are often done under the name of forestry and "selective logging," but it is little more than high-grading (Hall *et al.*, 2003). In many forest regions, certain animals have been so overhunted that their absence has created profound changes in forest habitat and composition. Examples can be found in Central Africa and the Amazon where the bush meat crisis has literally led to the extermination of ungulates, primates, and many other animals, many of which are important seed dispersers (Milner-Gulland and Bennett, 2003). In the case where the top predators have been eliminated because of predation on livestock, such as in North America, much of the forest can be overgrazed by large populations of ungulates (Côté *et al.*, 2004).

Degradation phenomena that can also be considered vegetative but often largely lie outside the control of the forester relate to various pests, pathogens, and invasives (see Chapter 26 on forest ecosystem health). In almost all circumstances, these impacts act to reduce or eliminate certain species of trees and plants, affecting species composition and structure of a forest; in some cases they can act to reduce or eliminate whole groups of species. The seriousness of the impact must be assessed quickly and action taken to mitigate the damaging agency as immediately as is possible. This is simple to state but in most cases very difficult to carry out.

Apart for categorizing degradation by vegetative and physiochemical phenomena, there are other parameters that can be used to systematically dissect degrading impacts on forests. To begin, vegetative impacts can be described as those effects that alter tree-species composition, density, distribution, and size class. Physiochemical impacts can largely be described as those degrading factors that affect the actual physical and chemical properties of the soil, thus affecting fertility and long-term productivity. Other than the obvious differences in categorizing degradation between vegetative and physiochemical, differences also exist between these categories in their degree of severity and in the nature of their timing. Vegetative degradation effects (structure and composition) are often chronic (ever-present or frequent), spreading and ongoing. The nature of invasives is a very obvious example. However, persistent overgrazing, or overharvesting of non-timber forest products or firewood are other examples. All have an effect on forest structure and composition that either simplifies one or the other, or both. Simply controlling the impact, or halting it, is sufficient to allow the forest to regain its original structure and/or composition through resumption of natural regeneration and successional process. At the other extreme are degradation events that severely impact a forest site to a degree that the forest's structure and composition has been eradicated, and the very nature of the soil has been altered to a level that the actual inherent fertility and structure of the soil have been reduced. This would be a dramatic example of physiochemical degradation (soil function and fertility). These kinds of degradation are acute, usually one-time events, such as land clearance for intensive agricultural cultivation or, even more severe, the removal of all the topsoil for surface mining of minerals.

Using the restoration staircase of Chazdon (2008) (see Fig. 25.1) the state of land degradation of an initially forested ecosystem can be categorized by different levels of severity. These levels are described in their order of severity from least to most severe. At each level, silvicultural approaches are given for their restoration.

Categories of Forest Degradation and their Restoration Treatments

Low-Severity Degradation: Rehabilitation through Assisted Natural Regeneration and Enrichment Planting

Assisted natural regeneration is mostly associated with chronic forms of degradation that affect the structure and the composition of a forest. Chronic forms of

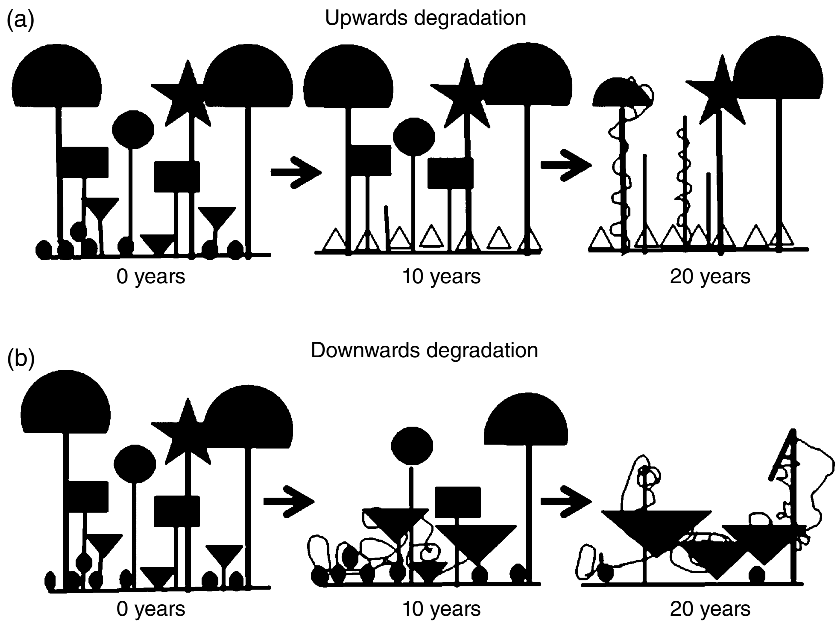


Figure 25.2 Profiles of a stratified stand canopy impacted by chronic disturbances. **(a)** "Upwards" degradation that first kills or changes the species composition and the structure of the forest understory, eliminating advance regeneration of canopy trees and understory shrubs and small trees. Over time, the continuous impacts eventually affect the canopy. *Source:* Adapted from Ashton *et al.*, 2001. **(b)** "Downwards" degradation effects that first influence the canopy of the forest, and in more severe cases, move downward to affect the understory. The mature forest canopy trees are depicted by black star or half-circle shapes. The subcanopy trees of a mature forest are black circles or rectangles. The advance regeneration is depicted by small black circles. The understory shrubs are depicted by inverted black triangles. Newly-recruited herbaceous weeds and invasive shrubs arising from the disturbance regimes are depicted as open triangles, and climbing vines as squiggly lines. *Source:* Mark S. Ashton.

degradation are numerous and often appear innocuous. They are repeated so frequently that the small incremental changes in forest structure and composition are hard to measure and detect without long-term plots. A number of important **chronic degradation** effects on forest structure and composition are listed here by either of two ways: (1) degradation impacts that are "upwards" by first killing or changing the species composition and the structure of the forest understory (e.g., bottom-up); (2) degradation impacts that are "downwards" that first affect the canopy of the forest, and in more severe cases move downward to affect the understory (e.g., top-down) (Fig. 25.2).

Vegetative Degradation that First Affects the Forest Understory

1) Overgrazing: ungulates (livestock or game animals) can impact the understory of many forests, particularly those in wet climates that have vigorous and stratified understories. They do this by compacting the surface soils and eating the groundstory vegetation, eliminating the herbaceous plants and advance regeneration or vegetative sprouts of the canopy tree species (Fig. 25.3a). Prolonged exposure will simplify forest composition and structure, progressively eliminating the ability of the forest to regenerate itself. In more seasonal drier forest types, grazing can actually have a beneficial effect, allowing certain species of non-palatable regeneration to be released from edible herbaceous and woody plant competition (Côté *et al.*, 2004).
2) Understory non-timber forest products (NTFPs): many non-timber forest crops found in the forest understory are either overexploited and eliminated with no prospect for sustainable management, or they are intensively cultivated, eliminating all other understory species, including advance regeneration of canopy tree species. Examples of overcultivation are numerous and include tropical forest spices and beverages, such as coffee, cardamom, and cacao, and temperate forest medicinals, such as ginseng, goldenseal, and ramps. The understory stratum is eliminated for two reasons: the actual cultivation of the crop purposely takes up all of the growing space (many crops are clonal and vigorously expand their growing space), and if the crop plant is herbaceous, the smaller understory trees and shrubs are removed to increase light and thus increase the productivity of the crop plant (Fig. 25.3b) (Ashton *et al.*, 2014b).
3) Understory plant invasives: plants that invade and usurp the growing space of forest understories are almost always clonal. Many are either dispersed by birds or on the fur of mammals, but many can be dispersed by humans and their vehicles, and establish first on trails. Like understory non-timber forest crops, they are very effective colonizers and expand and dominate the forest understory quickly, excluding other understory herbs and advance regeneration (Fig. 25.3c) (Royo and Carson, 2006). However, particularly in the western US, many light-seeded invasives (e.g., cheat grass, mullein) can actually establish on "restoration treatments" if the shade-tolerant conifers originally occupying the understory have been removed to reduce crown fires.
4) Use and control of fire: to exclude fire or to use fire is an important question and it depends very much on

the nature of the forest type and the documented presence of fire being an integral part of the forest dynamic. Humans have often used fire to clear out forest understories and to create fresh forage for livestock in moist temperate and tropical forests, where there is no evidence of fire being a part of the ecosystems without humans. In such cases, fire simplifies the forest structure, eliminating the fire-sensitive and often moisture-loving species and promoting a more open fire-tolerant composition. This can be deemed

(a)

(b)

Figure 25.3 **(a)** The browse line in a heavily impacted aspen stand. *Source:* D. Powell, U.S. Forest Service, Bugwood.org. Reproduced with permission from Bugwood.org. **(b)** A heavily impacted lower montane forest understory in south India where cardamom cultivation has removed all the understory herbaceous and woody vegetation. *Source:* Mark S. Ashton.

(Continued)

(c) (d)

Figure 25.3 (Continued) **(c)** A clonal understory of Japanese barberry in a New England hardwood stand. *Source:* L. Mehrhoff, University of Connecticut, Bugwood.org. Reproduced with permission from Bugwood.org. **(d)** Ingrowth of grand-fir beneath ponderosa pine because of fire exclusion. *Source:* J. H. Miller, USDA Forest Service, Bugwood.org. Reproduced with permission from Bugwood.org.

a form of degradation if the objective is to maintain a well-structured diverse assemblage of species (Fig. 25.3d) (Hessburg, Agee, and Franklin, 2005; Waring and O'Hara, 2005).

Policies of fire exclusion have set the stage for crown fires which are dangerous and almost impossible to suppress in dry temperate forest types. In stands of slash pine on the Atlantic and Gulf coastal plains, if there is no prescribed burning, "ladder" fuels of draped pine needles frequently develop on understory shrubs with waxy inflammable leaves. Serious problems have arisen in some localities where there is enough precipitation in one season to support the development of luxuriant stratified mixtures of species, usually conifers, coupled with a long extremely dry fire season. Large amounts of vertically distributed ladder fuels develop, especially if fires have been excluded for many decades. The situation can be aggravated if there are too many trees for the soil to support during drought years and many succumb to insect attack as a result. The resulting dead standing trees add to the supply of fuel and invite ignition by lightning strikes. Stands of this sort are common in the Sierra Nevada, the Rocky Mountains, and other places where fire exclusion has allowed fire-sensitive Douglas-fir and true firs to invade the lower strata of stands of ponderosa pine. The condition is not always the result of excessively successful fire control but was also common in earlier times. In nature, such stands regenerate slowly after the severe fires that occur at long intervals. However, neither the dangerous conflagrations nor the delay in restocking can be tolerated except in some remote wilderness areas.

Some forests include dry areas with low shrubby or grassy vegetation that is inflammable, yet adapted to re-sprout after fires. These are common in Mediterranean climates such as that of California with very long dry summers (Moreno and Oechel, 1994). About the only silvicultural treatment that can help on such areas is the reestablishment of vegetation after fires have occurred.

Methods of Restoration of Vegetative Degradation of the Forest Understory

In almost all cases, restoration of bottom-up degradation (overgrazing, intensive cultivation of NTFPs, understory invasives) is relatively simple; that is, to stop the chronic impacts or reduce them to a level that allows the vegetation to come back. Fire is a more complex issue that is dependent upon resumption if fire was excluded, or control if it was over-used. This depends upon the forest type, climate, and goals of the landowner. The following is a description of a number of restoration treatments

that can be used in response to chronic bottom-up degradation effects on forest structure and composition.

1) Overgrazing: the problem of overgrazing can be controlled by the removal of livestock, reduced populations of ungulates, and/or reduced periods of time to browse or graze by rotational grazing. All are solutions that allow the native vegetation to come back in the understory. The length of time that this needs to be done is dependent upon the growth and productivity of the forest type. For a moist temperate forest, noticeable establishment of herbs and advance regeneration can be detected within a few growing seasons. In certain cases, control of ungulate numbers and the period of when they browse is difficult and the only alternative is to prevent access by fencing, an expensive option, but the only one when the animals are free ranging. This is commonly done for high populations of roe deer or white-tailed deer in Europe and parts of eastern North America. If overgrazing has been so severe as to have eradicated various herbaceous groundstory species, underplanting may be the only remedy, and this needs to be done carefully on a microsite-by-microsite basis to ensure satisfactory establishment. Direct seeding may be suitable, but if large numbers of rodents are present, or the soils are compacted and the microenvironment overexposed from the overgrazing, then planting is the only alternative. Planting sometimes has to be done with supplemental organic and inorganic fertilizers. However, in certain circumstances the seed sources may already be there. In that case, all that is needed is the removal of grazing pressure and the lack of herbaceous composition is enough to result in an overabundance of regeneration.
2) Understory non-timber forest products: as with circumstances for overgrazing, the remedy is to stop the exploitation or cultivation of non-timber forest crops. Simple and deliberate prevention will be enough in many cases to allow other understory plant species to come back into the understory. Where clonal populations of NTFPs are so dominant that there are no native understory plants that remain, then partial eradication of NTFPs by site treatment (cutting, burning, or scarification) is needed to open up the growing space for either natural or planted regeneration of tree species and understory herbs. In cases where NTFP cultivation demands continuation, sustaining the successional process of the forest can be done by setting aside an intimate patchwork of reserve areas and microsites where NTFP cultivation is prohibited, and where advanced regeneration is purposely protected. By protecting individuals of advance regeneration and assisting the seedling through release cleanings within areas being cultivated, and by allowing NTFPs to be cultivated in a stand for a period, then allowing the stand to be rested for a period of time, a new cohort of tree seedlings can establish and then can be released before resumption of NTFP cultivation.
3) Understory invasives: like NTFPs that are clonal, site treatments need to be done to eliminate the invasive plants. The most logically easy and cost-effective way is to apply herbicides (see Chapter 18, Table 18.1). This can be followed up with understory plantings of the original plants or by allowing the area to revegetate from nearby seed sources. However, embarking on controlling invasives needs to be a judicious and careful choice. If there are nearby seed sources or it is already covering a wide area, the task ahead could take forever. Sometimes it is best to leave a sleeping dog lie!
4) Use and control of fire: any dead plant material can be fuel for wildfire if it becomes dry enough. Many of the silvicultural measures taken to reduce problems with forest fires involve the reduction of the fuels on which the fires feed. Some of the techniques of site preparation discussed in Chapter 7 are more important for fuel reduction than for facilitating regeneration.

The risk of damage from fire varies widely between different sites locally and between broad climatic regions. Almost any kind of forest vegetation will burn if it is ignited under the right conditions and the dry fuel is continuous enough to enable fires to spread. Before there were people, there were lightning fires. Almost every habitat has plant species adapted to fill growing space left vacant by fire. Some of the most humid regions usually have areas of dry soils, such as deep sands, that are subject to fire. Even swamps that always have standing water will burn if there is a continuous fuel blanket composed of dead, dry grass or similar herbaceous vegetation.

In many humid regions, wildfires are not important enough to warrant modifying the silviculture, although it is still necessary to suppress them. In some localities, particularly in the Pacific Northwest, where precipitation is high but occurs mostly as snow, forests regenerate from fire episodically, once every several hundred years. These regions have long dry summer seasons. This together with supra-annual periods, when winters repeatedly fail to provide an adequate snow pack to provide the meltwater to moderate the dry season, makes these forests highly inflammable during these years. It may not be possible to do anything silviculturally except for salvage and reforestation if a severe fire occurs. However, there is a middle category of places and forest types in which fuel-management measures will reduce the problems; sometimes it is not easy to decide where these places are or how far to go with the measures.

Fire itself is the most common and effective means of fuel reduction (e.g., longleaf pine, ponderosa pine, California oak woodland) but with concerns about adjacent communities and air pollution, it has to be practiced carefully.

The best solutions for susceptible western forests are to reduce stocking by heavy partial cutting, to thin the stands and eliminate ladder fuels that are subsequently removed and either chipped or burned in piles during the early spring. This is usually some kind of heavy low thinning or variable-retention thinning. After this has been done, it may or may not be necessary to carry out prescribed burning to achieve further fuel reduction or prepare for new regeneration. Multiple fires that are variable, not all should be low severity, have been shown to be the best way of maintaining forest conditions less susceptible to catastrophic fires and bark beetle outbreaks (Stephens *et al.*, 2012). This procedure has been used with remarkably hot fires to induce regeneration of the big-tree sequoia, the world's largest organism, in the mixed conifer forests of the Sierra Nevada. Not all natural forest types adapted to regenerate after wildfires are places where prescribed burning under existing stands is feasible. For example, in many stands of lodgepole and jack pine, the fuels are almost always so abundant and inflammable that most fires develop into uncontrollable crown fires. The usual solution in such cases is to create firebreaks to keep fires from getting large and then regenerate stands by planting or direct seeding after clearcutting and broadcast burning of slash, particularly when such forests are adjacent to human communities. Similar policies are followed with particularly inflammable stands of eucalypts in Australia, where mineral earth firebreaks are used to protect surrounding forests from natural or prescribed fire that arises within a regenerating area.

All of the plants that grow in forests are potential fuels, so complete elimination of all fuels is simply out of the question. Decisions must be made about the amounts and kinds of fuel that will be left or allowed to develop in stands. Among the factors to consider are the degree of risk of serious fires, their anticipated damage, and the prospective effectiveness of fire suppression. In localities where very damaging fires are common, these decisions become questions about what degrees of calculated risk to take.

The most far-reaching modifications of silviculture for dealing with wildfire risks are those in which fire-resistant species are grown and comparatively light periodic surface fires are used to keep dangerous amounts of fuel from accumulating. For example, ponderosa, red, loblolly, slash, and longleaf pines, and some other two- or three-needled pines are commonly grown as monocultures because of their fire resistance. Their tolerance of dry soils is also a factor in their adaptability to fire-prone sites. Because seedlings and saplings usually have yet to develop roughened fire-resistant bark, it may be necessary to avoid having stands with intricate intermingling of age classes, and making fire lines around many small units of area is very costly and difficult to administer. Sometimes the fires result in the development of a ground stratum of grass. Where this silvicultural policy is being followed, the fires must be frequent enough to prevent too much fuel from accumulating. It may be especially important to prevent vertical curtains of potential fuel from developing (Box 25.1).

Vegetative Degradation that First Affects the Forest Canopy

Chronic degradation effects from the top down are equal and opposite to those that are bottom-up. The following is a descriptive list of degradation impacts that affect the forest canopy forest canopy first and then with increasing severity move downward.

1) Selective logging: many people think that selective logging is a form of the "selection method" of natural regeneration and that it is a sustainable silvicultural technique (see Chapter 13). In most cases it is not, particularly in stratified, mixed stands of moist tropical and temperate realms where the canopy trees are largely long-lived shade-intolerant species. The practice of using diameter limits with selective logging, in which the largest trees are removed down to a set diameter, usually amounts to little more than high-grading the stand with little prospect of regeneration. This is because the seed source has been removed (the large mature canopy trees) and the seedlings, if in the understory, will be shaded out by in-growth from the remaining canopy. The continued application of diameter-limit cuttings, at periodic intervals, essentially diminishes the stature and the species composition from the top down (Fig. 25.4a) (Ashton *et al.*, 2001; Fredericksen and Putz, 2003; Ashton and Hall, 2011).
2) Insects and disease of forest canopy trees: both invasive and native pests can impose top-down degradation effects on forests in the same manner as selective logging and in the same forest types. Insects and diseases that kill or weaken overstory shade-intolerant, long-lived trees would be an example. Mixed, stratified, even-aged stands that are affected include canopy and emergent larch (larch sawfly, larch needle blight) beneath which is spruce–fir, canopy oak (gypsy moth) beneath which is beech, red maple, and sugar maple, and Douglas-fir (tussock moth, Douglas-fir beetle) beneath which is true fir, western redcedar,

Box 25.1 Restoration of California's oak woodland.

Introduction

Oak woodlands in the coastal hills and the foothills of the Sierra Nevada were once extensive diverse ecosystems. Since colonization by settlers and the gold rush, these woodlands have shrunk to a tiny proportion of the original range. Much of the oak was harvested for charcoal, mine timbers, and to clear land for grazing and "rangeland improvement." Only remnant oaks survive along riparian corridors as single trees in pastures, or within protected lands that are steep and remote.

Land trusts, the state government, and private landowners have all embarked on restoration programs for oak woodland for biodiversity conservation, riparian protection, and cultural preservation. Restoration has been compounded by regeneration failure for a variety of reasons. High numbers of acorns are taken by rodents, and seedlings can be heavily browsed and compete with more shade-tolerant species. Most California oak species require infrequent groundstory fires that allow top-kill and re-sprouting of oak, but kill the more shade-tolerant competing species. More intense crown fires will kill most of the adult oak tree species, except the most fire-adapted coastal live oak (*Q. agrifolia*) and interior live oak (*Q. wislizeni*), which can respond with crown sprouts. The most common species in moister sites include black oak (*Q. kelloggii*) and Oregon oak (*Q. garryana*), which may co-exist with more fire-sensitive conifers at higher elevations. Fires at these elevations may be one disturbance regime that prevents conifers from growing beneath and eventually replacing oaks. At lower elevations, fire is not required to maintain oak canopy dominance.

Restoration

When oak woodlands and parent trees are adjacent to the restoration site, natural regeneration may be the cheapest and most successful prescription. Waiting for a mast year to treat the area is the most effective, together with protection from grazing by fencing, elimination of vegetative competition with a brush cutter, and scarification. Light prescribed burning may be a tool in the right circumstance after seedling establishment to reduce competition.

When no nearby seed source for natural regeneration is available, collecting a local provenance that are likely to be better adapted to the site conditions, storing these, and then germinating the acorns and growing the seedlings in a nursery for several years, is the only alternative. Seedlings need to be inoculated in the nursery with ectomycorrhizae from top soil from an oak woodland. Seedlings should be out-planted when the rains come in the early winter. Individual seedlings can be netted to protect from browse, and planting sites need to be mulched to reduce desiccation and restricted to micro-topographic positions where there is shelter and soils are moist (Fig. 1). Soils that are shallow, or that have a hardpan need to be avoided. Moisture stress can be reduced by brushcutting or applying herbicide around the base of the planted seedling at intervals during the growing season for the first several years after planting.

Box 25.1 Figure 1 California black oak planted in an oak woodland restoration planting in Yosemite Valley. Seedlings have been planted in partial shade and protected by netting or tree shelters from deer browse. The area had a prescribed groundstory burn to reduce some of the invading Douglas-fir before planting. *Source:* Mark S. Ashton.

and western hemlock. Many canopy tree species that are affected by insect and pathogen outbreaks are initially stressed by abiotic precursors to infection, such as droughts and heatwaves (Fig. 25.4b) (Wargo, 1996; Saatchi *et al.*, 2013). There are also some common defoliators such as the western spruce budworm that can cause major forest health issues by defoliating the smaller shade-tolerant trees (e.g., subalpine fir, Engelmann spruce) that can grow beneath the shade-intolerant species.

3) Lianas and vines: many invasive vines and lianas often suffocate forest canopies from the bottom-up and the top-down, occupying growing space, and creating a load stress that eventually snaps canopy tree crowns and simply prevents any recruitment or ingrowth of trees into the canopy. Eventually the

(a)

(b)

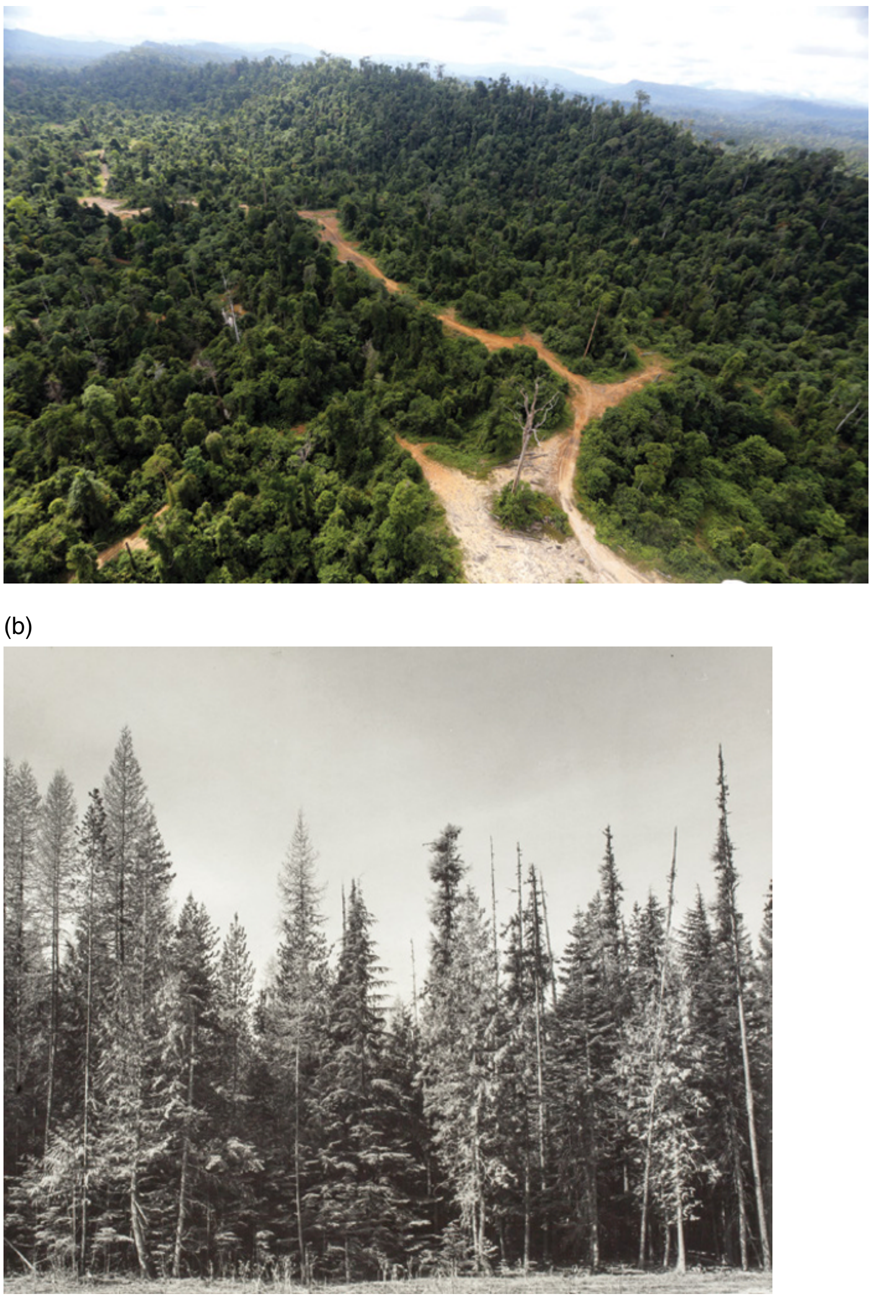


Figure 25.4 **(a)** Effects of repeated selective logging in mixed dipterocarp forest, Sabah, Malaysia, has led to top-down degradation of the forest canopy. *Source:* R. Butler 2015. Reproduced with permission from Rhett Butler/mongabay.com. **(b)** Stressed western larch above a sub-canopy of Engelmann spruce and subalpine firs in the northern Rocky Mountains. *Source:* Yale School of Forestry and Environmental Studies.

(c)

Figure 25.4 (Continued) **(c)** A kudzu vine-infested pine forest aggravated by thinning and canopy openings. *Source:* J. H. Miller, USDA Forest Service, Bugwood.org. Reproduced with permission from Bugwood.org.

canopy becomes very broken and incomplete. Examples in temperate moist forest types include climbing fern, bittersweet, and kudzu (Fig. 25.4c) (Schnitzer, Dalling, and Carson, 2000).

4) Wind: trees grow tall and the destructive power of wind increases exponentially with increasing distance above the frictional effect of the ground surface. Canopy and emergent trees are therefore the most susceptible to wind damage. The force exerted by wind also increases exponentially with wind speed. Many aspects of wind damage to forests have been reviewed by Counts and Grace (1995). Wind causes damage to trees by either breakage or uprooting of stems. In either case, the cause is compression failure of stems or roots on the leeward sides of trees. Such failures form because wood is weakest in its resistance to splitting. The failures appear along horizontal or diagonal planes on the leeward sides when tree stems are bent beyond the limit of their elasticity and a crushing action takes place. If compression failures have formed, the stem or root may later break at the uppermost compression failure (Mergen, 1954). If the failure is in the stem, it often breaks about halfway between the base of the crown and the ground; if the uppermost failure is in the supportive roots, the tree will uproot if subsequent winds push it over. The compression failures impair the elasticity of the wood and cause more strain on the half of the tree stem that is under tension. If the wind force becomes great enough, the whole stem breaks, leaving a splintery tension failure on one side of the break and the brash compression failure on the other.

5) Ice storms: snow and ice loading on the canopies of moist temperate forest is an important impact that disproportionately affects the finer-branched canopy trees as compared to those canopy trees with coarse branching patterns. Trees in the subcanopy and understory are less exposed to ice and snow deposition and thus are less susceptible to branch breakage (Covey, Barrett, and Ashton, 2015).

Methods of Restoration of Vegetative Degradation of the Forest Canopy

Restoration of top-down degradation (selective logging, insects and disease, lianas, wind damage, ice storms) is a relatively more difficult task than those techniques used for bottom-up restoration. Chronic impacts to the canopy have profound long-term influence on forest structure and composition that will take a whole new generation of trees to eventually remedy.

1) Selective logging: forests that have been selectively logged have two trajectories for restoration. If the logging has not been intensive and has not had repeated entries, usually simply allowing the forest to rest and recover its structure, without the primary timber trees that were logged, is all that is needed. Supplemental actions could include liberation release treatments to ensure canopy tree saplings beneath the subcanopy can satisfactorily grow into the canopy (Pariona, Fredericksen, and Licona, 2003; Shono, Cadaweng, and Durst, 2007). In instances where certain timber-tree species have been depleted, the only alternative is enrichment with line or cluster

plantings, taking advantage of openings that already exist, or creating openings, if absent, to allow the seedlings to grow into the canopy. Periodic cleaning would need to be made to free the plantings from competitors. Enrichment planting guidelines need to ensure that the opening size matches the shade tolerance of the selected seedlings, and that the species planted are appropriate for the site (Ashton *et al.*, 2001). Care is needed in species selection because many late-successional timber trees are site restricted, particularly in moist tropical and temperate forests. On occasion, particularly in the tropics, liana and vine control along the planting lines is necessary.

In circumstances that are more dire, where selective logging has led to a complete loss of structure and stratification and the forest is now enshrouded by vines and coppiced understory shrubs and trees, the only remedy is to start again by cutting the forest back to the ground and allowing any advance regeneration and seedling sprouts of the original forest canopy to be released at the same time as the pioneers seed in. This would be like a one-cut shelterwood where the forest stand is starting off at the reinitiation stage. The intention is to re-secure complete growing-space occupancy and allow the stand to move into stem exclusion and crown stratification in a uniform way. At first thought, this often seems counter-intuitive until there is recognition of the competition problems with vines and ingrowth from subcanopy strata that relatively shade-intolerant canopy tree saplings must face (Ashton *et al.*, 2001, 2014c).

2) Insects and disease: the remedies for dealing with diseased and dead canopy trees are varied, depending upon the ecology of the pathogen or insect. This makes things very specific to the nature of the forest circumstance, but some generalizations can be made given this caveat. Choices can be categorized into partial cuttings and associated treatments, starting again through regeneration, and leaving alone.

Partial-cutting treatments are ways of controlling dead and dying trees, and include both salvage cuttings, cutting the already dead or infected trees, and sanitation cuttings, cutting trees that are predisposed to infection or are taken to control spread (see definitions of sanitation and salvage in later sections of Chapter 26). After treatment, this leaves a more heterogeneous canopy structure and a simpler composition because of the cutting, particularly if the diseased trees are all a specific species (Waring and O'Hara, 2005). Enrichment planting in the manner described to restore a selectively logged forest can be done to supplement forest composition. However, it is important to select canopy tree species that are resistant to insect or disease. Alternatively, another tool that can be used in sanitation is the use of fire through prescribed burning. Groundstory burning often kills many pests and promotes a less humid understory that is more inhospitable to fungi. Using fire in fire-dependent forests of the interior western and southern US is one way of maintaining a greater forest resistance to pathogens and insects. Like fire, thinnings in overstocked stands can reallocate resources (light, soil moisture) to surviving trees that increases their vigor, and in that way their resistance to infection (Mutch *et al.*, 1993; McCullough, Werner, and Neumann, 1998; Waring and O'Hara, 2005).

Sometimes, like degraded stands that have developed from repeated selective logging, if the situation is dire, completely cutting the whole stand and starting again may well be the best solution by readjusting the dynamic back to the start. Site treatments that include mechanical scarification and/or burning are often used to control damaging pests and diseases when a new stand is being regenerated either naturally or by planting.

The last option is to leave the stand alone and let nature take its course. All too often, foresters are quick to salvage trees and forests, and that action, in the end, may not be needed. Many trees can recover, depending upon the insect or disease. This is a very valid option and one that is sometimes the cheapest and with the best result. An example from the northeastern US is the case of the eastern hemlock and the hemlock wooly adelgid in central New England and New York. The adelgid is held in check by cold winters and the hemlock is more resistant to infection on moister, cooler sites. Had foresters efficiently and intensively cut the hemlock in the name of sanitation and salvage harvests, an important component of the forest that actually had the ability to persist would have been lost (Foster and Orwig, 2006). Even in death, trees can be beneficial in creating snags, woody debris, and the incremental regrowth of a new forest, minus the tree species that succumbed to the insect or pathogen.

3) Lianas: the simplest control of lianas is to cut them, but their proliferation is usually related to ongoing disturbance and incomplete canopy occupancy. This kind of disturbance and canopy structure provides climbing vines and lianas an opportunity to access the canopy. Simply cutting lianas is a short-term control. Ensuring that the forest canopy is completely "sealed" by the crowns of the competing trees is a more efficient long-term way of excluding lianas. Moving to an even-aged regeneration method or one which is more strongly episodic (two- or three-aged) is one way of excluding lianas and vines from the forest canopy. This usually means simply cutting the broken canopy to the ground and starting over, while taking care to control any lianas or vines that might establish by

applying herbicide judiciously during the period when the regeneration is released.

4) Wind: damage from wind can be reduced by: thinning to increase the taper and strength of individual tree stems; avoiding the creation of local accelerations in windspeed; and using strip-cutting methods in which successive cuttings advance from leeward to windward. In planning for silvicultural measures to reduce wind damage, it is very important to know the directions from which the damaging winds are likely to blow. These directions are not necessarily the same as those of the prevailing winds, although it helps to recognize that tree stems tend to strengthen themselves against the winds from the directions that predominate during the seasons when wood formation takes place. In temperate North America, the most common direction of winds in major storms during the growing season is from the southwest. The main exception is found along the Atlantic Coast where southeast or southerly winds blowing by the shortest distance from sea surfaces during hurricanes are most dangerous, even though the prevailing winds are westerly. The very destructive winds associated with tornadoes may blow from almost any direction. They are so powerful that there do not appear to be any measures that can be taken to mitigate their effects, other than post-storm salvage. Use of the strip-selection system to divert damaging winds up and over a stand can be one approach (Fig. 25.5). The stands that are most endangered by wind are those growing on slopes exposed to winds that blow unobstructed across broad expanses of water or level terrain. Stands on very shallow soils are also vulnerable to uprooting. Although heavy, early, and frequent thinning may help, it is sometimes necessary to grow trees on short rotations so that they do not get very tall. It also helps to use species with relatively strong wood because these resist not only stem breakage but also the failures of supportive roots that lead to uprooting.

When the pathways of moving air are constricted in either the horizontal or vertical dimension, the windspeed is increased because unchanged volumes of air are forced into narrowed passages. Small accelerations in windspeed can be significant because the force of moving air varies with the third or fourth power of the speed. Windspeeds of 90 miles/hr (145 km/hr) represent the approximate threshold of severe damage but some damage can occur at much lower speeds; few trees can withstand speeds in excess of 120 miles/hr (193 km/hr), such as the winds of tornadoes.

When a stream of air passes up over a ridge or mountain range, its passageway is constricted from below and its speed is accelerated. The same effect takes place when the air moves through any sort of horizontal gap, whether it be a gap in the terrain or a gap in the margin of a stand of trees. The terrain cannot be changed, but it is silviculturally possible to shape the edges of stands in ways that reduce the possibilities of dangerous accelerations of the wind.

In most kinds of terrain, the wind damage associated with topography is most common and worst on the windward slopes where it would intuitively be expected. However, if the slopes are exceedingly steep, as in some parts of western North America, it is often worst just leeward of the ridge crests. This is because of gusty downbursts of air that take place in a turbulent zone on the lee sides of the crests. The same effect can result when stormwinds collide with tightly closed vertical stand edges; the edge trees may withstand the wind, but the weaker ones behind them are hit with downbursts. One way of dealing with borders of stands that are undergoing partial cutting is to

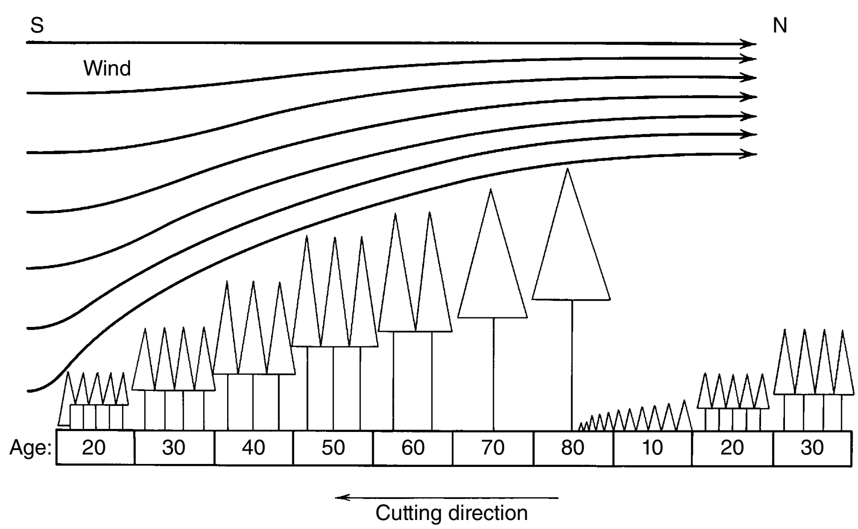


Figure 25.5 A depiction of strip-selection cutting to minimize wind damage. The cross-section is along a north–south axis through part of a stand managed on an 80-year rotation. The stand is streamlined against southerly winds and regeneration is also protected from the direct rays of the sun. Cutting progresses from north to south and the 80-year-old strip is about to be replaced. *Source:* Yale School of Forestry and Environmental Studies.

leave strong, scattered trees in broad belts as in uniform shelterwood cutting. This dissipates some of the force of the wind gradually, rather than abruptly. However, the main consideration is avoiding the creation of patterns of stand arrangement that create or accentuate constrictions that cause windspeeds to accelerate.

Sequences of cutting in successive strips that advance from leeward to windward can create the streamlined pattern of stand arrangement and reduce the risk of downbursts. In this sort of **strip-selection cutting**, appropriately long periods of years must be allowed to elapse between the cuttings, and it is necessary to adhere to the schedules (Fig. 25.5). This approach can be combined with efforts to protect tender seedlings against exposure and the invasion of undesirable pioneer vegetation in **strip-shelterwood cutting**. Where combinations of protection from sun and wind are desired, the strips must advance in a direction that is a compromise between the direction from which dangerous winds blow, and the direction of the midday sun. In many cases in the northern hemisphere, this means that the strips advance from northeast to southwest. Quick replacement of stands by clearcutting in narrow, quickly advanced strips does not produce streamlining effects, but it can help to advance them from leeward to windward. In any sort of strip-cutting, it is highly desirable that the windward edge of the last strip that is to be cut, should be composed of trees that are strong enough or deeply rooted enough to be unusually windfirm.

5) Snow and ice: the best way to keep trees from breaking under the weight of adhering snow and ice is to develop strong trees with symmetrical crowns. Where either people or the forest itself are threatened with snow avalanches, permanent selection forests can be maintained so that the snow is kept anchored in place or diverted after it starts to slide. Small trees growing in gaps in stands may suffer frost damage because the small openings become frost pockets. If there is wet snow, it may accumulate on evergreen branches around the openings, and crush small trees when it suddenly cascades down onto them. In extreme cases, shelterwood cutting or the use of nurse crops may be necessary to protect regeneration from frost damage (Groot and Carlson, 1996).

Medium-Severity Degradation: Rehabilitation through Natural Regeneration, Direct Seeding, or Planting

Unlike chronic degradation that occurs from repeated or ongoing impacts to forests that can usually be remedied by assisted natural regeneration or enrichment planting, acute degradation (medium severity) is a one-time event that is more intensive, and can dramatically change the successional process or even convert a forest to another vegetational state. Reforestation from nearby seed sources that establish natural regeneration, the planting of seedlings, or direct seeding are the main mechanisms for restoration.

There are different levels of acute degradation that can be further subdivided. One subdivision is acute degradation phenomena that eradicate the vegetation and change the successional process but that do not dramatically alter soil structure and hydrology. This kind of **acute degradation** can be considered **vegetative**, mostly affecting forest structure and composition.

Acute vegetative degradation can be further classified as **sub-lethal** and **lethal**. As implied, sub-lethal forms of acute structural degradation can dramatically change a successional process and the vegetation composition, such as land-use conversion from a forest to a pasture. However, if the pasture is left alone, it has the ability to revert quickly back to second-growth forest because of nearby seed sources from remaining forest fragments and pasture trees. Lethal is an acute structural and compositional form of degradation where all forest fragments and isolated trees have been eradicated primarily because of a more intensive and extensive agricultural land use or medium-severity fire. Forest recovery is obviously much slower, primarily because of an absence of seed source and shelter.

Acute Vegetative Degradation (Sub-Lethal)

Sub-lethal degradation can be further divided into two kinds of forest clearance that may seem innocuous but in actual fact are very different. Forests that are cleared for agricultural cultivation create a soil and aboveground microsite after agricultural abandonment that is very different from forests that are converted to pasture.

Forests that are cleared for agricultural cultivation can be considered a form of sub-lethal structural degradation to forests in the sense that they obviously clear the forest structure and composition in order to cultivate. Many forms of this occur across the world, primarily by smallholders and subsistence farmers who may cultivate land for a cash crop, but are concerned with cultivating or protecting trees that provide them with a range of additional values. Obvious examples include coffee, tea, and cocoa growers. Tilled cultivation, such as swiddening and market gardens for vegetables are other examples. Under these circumstances, soils are prone to erosion and nutrient loss, but when and if the lands are abandoned, the substrate is a mineral soil that is ideal for colonization by small-seeded pioneers (Piotto *et al.*, 2009).

Forests that are cleared and then sown with pasture grasses that can build up a thick sod create a very different regeneration microsite after field abandonment.

Figure 25.6 After 20 years of field abandonment, eastern white pine has colonized large parts of an old field. *Source:* Mark S. Ashton.

Grasses can remain dominant for long periods of time, often maintained by a fire cycle that was never present when the land was in forest. The nature of natural regeneration can be much slower and is dominated by a very different group of species. In eastern North America, lands that were old pastures have first been colonized by a sequence of conifers that dominate this process at different latitudes from Labrador, Canada to Nicaragua, and that give way to the original hardwood species that were there before land clearance. The conifers have a set of adaptations that provide them a unique advantage over most of their hardwood competitors for this kind of circumstance (drought tolerance, unpalatability, and ability to germinate on a thick root sod) (Fig. 25.6).

Restoration of Lands that have Acute Vegetative Degradation (Sub-Lethal)

Given social circumstance and condition of the field after abandonment, both cultivated field and pasture will revert back to second-growth forest, usually without the helping hand of the forester, given some time and the absence of fire. On old cultivated lands, light-seeded, short-lived pioneers can colonize almost immediately after cessation of cultivation, because of the ubiquitous presence of their seed-rain from wind, small birds, and bats (Holl and Lulow, 1997; Griscom and Ashton, 2011; Chazdon, 2014). Heavy-seeded species can be there already in the form of seedling sprouts that were never weeded out in cultivation, or they can establish with the aid of animals and nearby seed trees from forest fragments and shade trees (Holl and Lulow, 1997; Chazdon, 2014). For wildlife habitat or watershed protection, this may be all that is necessary, given the fact that the wildlife (by seed dispersal) often created the young forest and their own preferred habitat in the first place (Ashton *et al.*, 2001). However, for some commercial tree species that are site restricted and have poor dispersal abilities, it may be necessary to enrich species composition by line plantings among the young regenerating second-growth trees. Repeated cleaning is likely necessary to ensure survival (Ashton *et al.*, 2014c).

Old pastures will take longer to regenerate and follow a relay floristics model, as compared to initial floristics for abandoned tilled fields (see Chapter 5 for a description of initial versus relay floristics). Usually a native conifer (or sometimes a hardwood) adapted to the extreme conditions that grass creates, can germinate successfully, establish, grow, and shade out the grass sod out. Germination conditions are then more hospitable for small-seeded tree species that then establish. The cover that is provided also allows animals to disperse the heavier-seeded species from nearby shade trees and forest edges. A second forest cohort will thus establish beneath and eventually replace the old-field colonizers. This work was first reported throughout eastern North America in the early part of the last century, when old fields were a dominant part of forest recovery within this region, but this is a much more

(a) (b)

Figure 25.7 **(a)** An old-field mosaic of forest fragments, shade trees and hedgerows in Costa Rica. **(b)** A fire-maintained alang-alang (*Imperata cyclindrica*) grassland on former mixed dipterocarp forest that had been selectively logged and then repeatedly burned. *Source:* **(a, b)** Mark S. Ashton.

widespread phenomenon in temperate and boreal forest types of western North America, tropical Central and South America, and Eurasia (Fig. 25.7a). However, pastures and livestock are not an important cultural or land-use practice in much of southeast Asia. Instead, mixed dipterocarp rainforest that has been repeatedly selectively logged has allowed fires started by humans to convert the forest to fire-maintained grassland (e.g., alang-alang) (Fig. 25.7b) (Garrity *et al.*, 1996). Under these kinds of conditions, emulating old-field pine succession by introducing fire-tolerant species like Caribbean pine is one possible answer. Although the pine is non-native to the region, it can provide a temporary window of time to act as a nurse for native vegetation. The pine can first shade out the ferns and grasses, and along with controlling fire, can then facilitate establishment of site generalist late-successional native tree species dispersed by animals and small-seeded pioneers from adjacent forest fragments (Ashton *et al.*, 2014c). In fact, non-native plantations of several timber and pulp species have been shown to facilitate establishment of native forest regeneration beneath (Parrotta, Turnbull, and Jones, 1997). Enrichment planting in openings made within the pine, or as underplantings beneath the pine, can establish late-successional tree species that are more site restricted or have poor seed dispersal (Box 25.2) (Ashton *et al.*, 1997, 2014c).

Acute Vegetative Degradation (Lethal)

Like acute non-lethal structural degradation, this kind of degradation is related to land clearance, but it is usually at a scale that is dramatically larger and more efficiently intensive, removing all remaining seed sources and forest fragments with the singular focus of cultivating one crop, or raising pastured livestock for an industrial-sized farming program. The landowners are more commercial and larger in focus, and more invested in higher crop productivity of a few commercial species. Current agricultural and plantation systems are examples of this. Their high efficiency in producing pure crop yields comes at a sacrifice to remnant native forest diversity and seed sources, wildlife habitat, water quality, and access to open space.

In other forested regions, extensive areas of medium- to high-severity wildfires that have no seed source remaining for establishing a regenerating forest would be considered to fit this category of degradation. In western North America, the lethal disturbance equivalent to intensive land clearance for agriculture is high- or medium-severity fire. In the last half century wildfires have become much larger with extensive high-severity patches that do not regenerate quickly. In these cases many revert to shrublands dominated by clonal plants like ceanothus. In the last 10 years some of the most severe and extensive fires on record have occurred. Complete mineral soil exposure post-fire has often promoted top soil loss and sheet and gully erosion.

Restoration of Lands that have Acute Vegetative Degradation (Lethal)

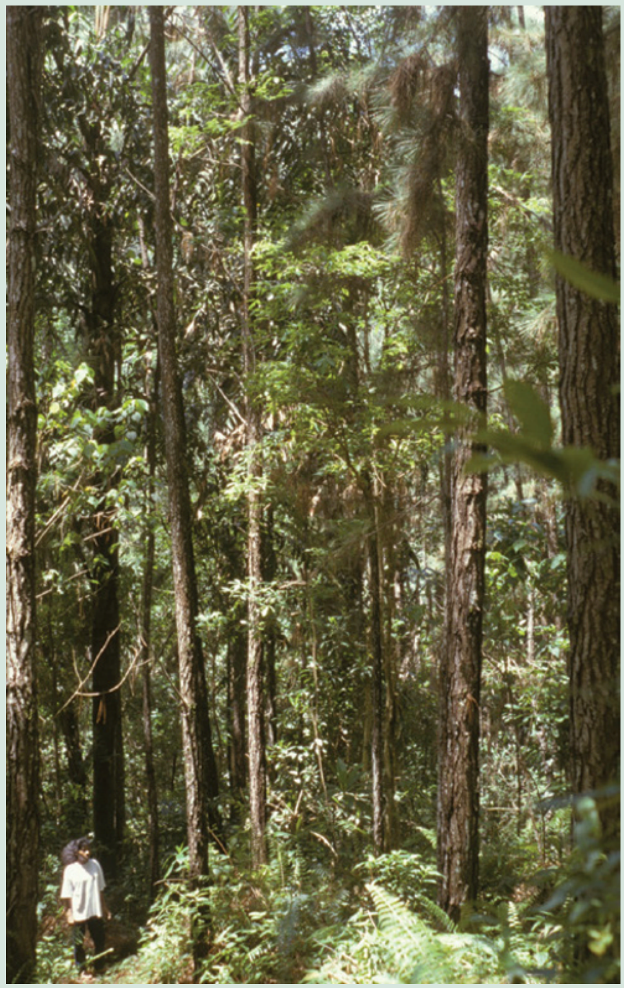
Under these kinds of circumstances, forest soils can be changed but not substantially. In many regions, soils are so marginal that landowners are encouraged to abandon the intensive management practice being used, and to

Box 25.2 Forest rehabilitation on old agricultural lands using exotic plantations.

In many regions when agricultural lands are abandoned, the cropland often does not allow the establishment of a new second-growth forest, but instead reverts to grass or fern lands (e.g., alang-alang (*Imperata cylindrica*) that can be continuously perpetuated by fire) (Cohen *et al*., 1995; Garrity *et al*., 1996). For restoration, this poses a large and pervasive problem with old agricultural lands in many regions of the world. Studies have shown that one mechanism to secure second-growth native forest is to plant exotic fast-growing, fire-adapted tree species in plantations. These plantations are surrogates of the "old-field pine" succession model, found in many temperate forest regions of Eurasia and North America. Studies on *Acacia mangium* plantings in Indonesian Borneo (Otsamo, 2000; Norisada *et al*., 2005); *Eucalyptus* in Brazil (Parrotta, 1997); and teak (*Tectona grandis*) in Thailand (Koonkhunthod, Katsutochi and Tanaka, 2007) have all recorded understory establishment of native rainforest species. There are many reasons for this. Some plantation trees attract seed-dispersal agents such as birds and bats because of their fruit (Holl and Lulow, 1997; Zahawi *et al*., 2013) or the plantation trees serve as attractive structures for perching and roosting sites of birds and bats (Holl, 1998; Jones *et al*., 2004). Studies have also demonstrated that the soil surface beneath some plantation species provides suitable seedbed conditions for germination by shading out the original competing grasses and ferns (Lamb, 1998), and some plantation species have been shown to increase soil fertility through nitrogen enrichment, increased soil carbon, and higher soil moisture availability, making the soil more hospitable for native species establishment (Fisher, 1995; Lamb, Erskine, and Parrotta, 2005) (Fig. 1).

Studies have also shown recruitment of rainforest species beneath plantations to fail. Reasons include: (1) cycles of groundstory fire that can occur beneath fire-prone plantations (*Pinus* spp., Goldammer, 1988; *Eucalyptus* spp., Kanowski *et al*., 2005); (2) allelopathy from the leaf litter of plantation species (e.g. teak, Healy and Gara, 2003; *Eucalyptus*, Lamb, 1998); (3) deep shade produced by the dense canopy of plantation species (*Acacia mangium*, Otsamo, 2000); and (4) decreased soil-moisture availability from root competition with plantation tree species (*Eucalyptus* spp., Jackson *et al*., 2005). Finally, many studies have shown that some plantation species (*Acacia mangium*, *Pinus* spp.) to be invasive if not carefully tested for ability to naturalize.

Plantations have also often been successfully used to transform former agricultural lands back to native forests by enrichment planting of native trees species beneath the canopy or within openings (Fig. 2) (Ashton *et al.,* 1997). This kind of approach involves more intensive and costly interventions and supplements to the natural regrowth of native vegetation that often requires treating the plantation by thinning and/or making canopy openings to obtain the preferred growing conditions for the planted native vegetation. By purposely planting particular species at a desired spacing, the forester can more predictably obtain the desired composition and structure to produce commodity products or wildlife habitat, as compared to volunteer regeneration that might more randomly establish.



Box 25.2 Figure 1 Second-growth natural recruitment of pioneers and site generalist late-successional rainforest tree species beneath a 20-year-old Caribbean pine plantation in southwest Sri Lanka. *Source:* Mark S. Ashton.

(*Continued*)

Box 25.2 (Continued)

Box 25.2 Figure 2 An enrichment planting within strip-cut openings of a 20-year-old Caribbean pine plantation in southwest Sri Lanka. Photographs depict **(a)** before planting, **(b)** growth of rainforest plantings of site-restricted late-successional canopy, and understory tree species at 8 years. *Source:* **(a, b)** Mark S. Ashton.

think about restoration strategies for obtaining higher social and economic values than the present conditions allow. To restore forests on such sites with an absence of a native seed source, leaves planting as the only alternative. Even then, planting means selecting trees that can tolerate low-fertility droughty soils in open desiccating environments (Box 25.3) (Wishnie *et al*., 2007; van Breugel *et al*., 2011). Many of the native tree species may not be adapted to such conditions given the novelty of modern degradation and their inherent maladaptation to the severity of the land clearance (Ashton *et al*., 2014c). Once the right site-hardy trees have been selected, the alternative successional pathways can be numerous (e.g., single-species, multiple-species, single-aged successional mixtures, multiple-aged successional mixtures) depending upon economic and social goals. Some species may be planted for timber harvests, others for improved wildlife habitat, and still others to increase system resilience to unpredictable changes in climate, reducing the risk of disease, or to diversifying markets and reducing market risk (see Chapter 16 on plantations). An alternative to planting is direct seeding. To do this, numerous seeds must be bought or collected (sometimes of many species) for a region. Seeds must be prepared, cleaned, and then mixed in a slurry that can be broadcast at the beginning of the growing season on the prepared reforestation site (Box 25.4).

In places where wildfires are so severe and extensive that they have eradicated the capacity of a new forest to start, the only alternative is to directly seed stabilizing mixtures of native grasses and herbs (often from the air) and then to follow up with tree planting. Today, particularly on public lands in the western US, plantings are often at variable densities that have an irregular spatial

Box 25.3 Native species planting trials.

Many regions of the world have little information on the growth and survival of native tree species. To date, a very few species have been used in plantations, even though people and regions have very divergent and varied goals and objectives in planting trees. Planting more tree species in reforestation programs may increase resilience of the plantings to insects and diseases, diversify markets for products, and increase the habitat conservation value for wildlife. Many reforestation projects fail because of bad species-selection decisions in tree planting. Many trees species selected are planted on the wrong sites and soils, and in incompatible climates. The first task that should be done is testing large numbers of species in planting trials that serve to screen for the best performers. This has long been recognized but is usually never done. Very few large trials have actually been established, especially across the tropics. To assess growth performance of native species, planting trials need to be done to measure survival and growth and the basic attributes of canopy structure, morphology, and susceptibility to herbivory, insects, and diseases. Plantings need to be designed as a common garden across a representative range of climates and soil types (Fig. 1).

Box 25.3 Figure 1 Seventy-five tree species representing a variety of social and ecological values planted in multiple blocks of 25 individuals stratified by topographic position (ridge, mid-slope, and lowland). The plantings are designed as a common garden to monitor the maximum potential growth of each species in relation to soil and topographic position in open conditions without competition from neighbors. This planting is one of four, each located on a different soil type and climatic region of Panama. These experiments are part of the Program in Native Species Restoration (PRORENA), managed jointly between the Smithsonian Tropical Research Institute and the Yale School of Forestry and Environmental Studies to evaluate the reforestation potential of native species on deforested lands in Panama. *Source:* Mark S. Ashton.

pattern to create greater structural heterogeneity and openness, thereby increasing the groundstory herbaceous diversity and wildlife habitat.

High-Severity Degradation: Forest Reclamation

Acute Physiochemical Degradation

Where land clearance has physically changed the hydrology, either purposely (i.e., irrigation, drainage) or by poor practice (topsoil erosion, soil compaction) from a baseline norm, this kind of **acute degradation** can be considered mostly **physiochemical**. Degradation that affects soil function and fertility can be considered the most severe, and thus the most difficult kind of degradation to facilitate and store vegetation recovery (Ashton *et al.*, 2014a, c).

The most dire circumstances that merit intensive and costly measures for forestland restoration are those lands which have been stripped of their topsoil or have been dramatically changed. There are many examples that include: (1) severe sheet erosion from poor agricultural practices applied on the wrong soil and in the wrong climate; (2) surface soils that have been completely changed

Box 25.4 Restoring rainforest by direct seeding, Xingu, Brazil.

The upper basin of the Xingu River is in the southeastern part of the Amazon and within the state of Matto Grosso. Much of the land has been cleared for ranching and agriculture that cannot be sustained (Bloomfield *et al*., 2012). Using the degradation classification, it would be considered acute, lethal, and widespread, with little to no seed source of the original forest remaining. There are a number of restoration/reforestation "pathways" that can be taken, depending upon the landowner and their values. The Socio-Environmental Institute (Instituto Socioambiental, ISA, in Portuguese) together with other organizations, including the Association of the Xingu Indigenous Territory (ATIX), the Forum of Mato Grosso for Environment and Development (FORMAD), and the State University of Mato Grosso (UNEMAT), have embarked on an ambitious program of forest restoration (Gravina *et al*., 2015). They have been working with indigenous peoples, small landowners, large ranches, and agricultural farms. The focus has been to work with the development of compatible agroforestry systems for indigenous peoples and small landowners (see Chapter 31). These landowners have more manual labor available and need a mix of both income and food from their land. However, with larger landowners (farmers and ranchers), the partnership has been working with enrichment planting and assisted natural regeneration where such regrowth exists, but where it does not, primarily because of an absence of seed source or dispersal agent, they have been primarily relying upon direct seeding to accomplish regeneration establishment on large areas using mechanized systems (Fig. 1).

Direct seeding offers some advantages when seed predators are absent. The seed is planted in a mulch and in very diverse mixtures (Campos-Filho *et al*., 2013). This allows for the most successful species to germinate and colonize a site and allows species selection to be a process of competition for resources given the nature and inherent variation within the site (Fig. 2). This is a cheaper alternative that relies much less on the technical knowledge of species autecology that planting requires. The denser regrowth also creates a variety of habitats, better root development and drought resistance, and cheaper and more efficient method as compared to planting, particularly if the silvicultural knowledge of species site selection and nursery propagation is lacking. The large demand for seed is met by the "Xingu Seed Network" in which smallholders and indigenous peoples collect, process, and sell the seed to the reforestation enterprises. The site preparation of fields to be reforested first requires use of a herbicide to kill the exotic grasses. The soil is then plowed several times to increase infiltration and to reduce compaction. Seed of up to 30–40 species of rainforest trees, comprising a mixture of early- and late-successional trees, are sown in a slurry before the start of the wet season. The seed mixture generally includes 70 species: one-third pioneer, one-third late-successional, and one-third annual and bi-perennial nitrogen-fixing legumes (Campos-Filho *et al*., 2013).

Box 25.4 Figure 1 Direct seeding using a tractor on a plowed field that has been prepared for seeding up to 70 species of seed. *Source:* Instituto Socioambiental. Reproduced with permission from Instituto Socioambiental.

Box 25.4 (Continued)

Box 25.4 Figure 2 A direct-seeded reforestation site 5 years after seeding. *Source:* Instituto Socioambiental. Reproduced with permission from Instituto Socioambiental.

or lost from mining; (3) severe erosion and compaction on abandoned lots of urban areas; (4) completely new and novel soils on reclaimed landfills; (5) severe surface soil toxicity in agriculture from salinization of irrigating soils in dry climates; (6) toxic chemical spills from such structures as oil pipelines; and (7) changes in salinization and tidal inundation from aquaculture that kills mangrove and swamp forest.

Mining activities are probably the most extensive and the most relevant of all listed activities that severely impact forests and soils. Mining comes in different forms that can be categorized as area mining, open pit mining, contour mining, and mountain-top removal. Lands lost to mining is small compared to total areas of countries (0.01% Canada, 0.08% Peru, 0.1% US, 0.26% Australia, 0.45% Brazil), but even then this actually means millions of acres (hectares) of land that are permanently lost to other uses, with exponentially larger repercussions on long-term hydrological change, and water-pollution problems that are difficult to quantify in the near-term (NRC, 1998; Arbogast, Knepper, and Langer, 2000; Minerals Council of Australia, 2010).

Restoration of Lands that have Acute Physiochemical Degradation

Restoration in these circumstances really means developing different novel soils and vegetation structures that include species combinations that can reclaim the site and return the land to a greater productivity for human use than before. The greatest engineering effort is usually in ensuring that surface and groundwater hydrology is functional, and that leachate, salts, and toxic chemicals are not escaping downstream into other parts of the watershed. In the case of mining and landfills, this means careful land reclamation that recreates the soil formation from the bottom up, placing the saved topsoil back on top of a changed landform that allows subsurface water to flow freely back into an intact watershed (Boxes 25.5, 25.6). Soils are modified to maximize infiltration by fortifying them with organic mulches and protected by groundcovers (Box 25.7). On steep slopes armored drainage ditches are necessary to catch excess surface water and divert it off site as quickly as possible. The approach taken in mining reclamation is the same, but with lower soil-modification inputs and water-control devices, for agricultural and urban sites with severe sheet erosion and compaction.

Desalinization of agricultural dry lands and restoration of riparian and coastal forests such as mangroves may appear disparate but they have one common phenomenon, salt accumulation because of a dysfunctional hydrology. In both cases, the hydrology needs to be restored by flushing and diluting the salts away to levels that are non-toxic to planting establishment (Box 25.8).

Box 25.5 Mine reclamation in West Virginia.

Surface mining or open-pit mining requires reclamation after the ore, coal, or mineral has been extracted. The kind of site degradation that occurs can be considered the most severe, with complete loss of structure and function to the original forest ecosystem. The restoration plan requires rebuilding the landform from scratch. This means first recreating an intact and integrated hydrology with a stabilized surface and sub-surface substrate with the use of contouring, then identifying and recreating riparian flow areas with catchment basins, and finally seeding a landscaped soil surface.

Historically in West Virginia, the common practice was to seed with tall fescue grass and invasive legume *Sericea lespedeza* to quickly colonize the open surface. Black locust (*Robinia pseudoacacia*) was often either sown or planted with the mixture. This practice was very effective at securing and protecting the ground surface but was prone to stagnating as permanent grassland because of the thick sod that developed, preventing other seed from germinating, and often because of an absence of any nearby forest tree seed sources. The black locust, because of its nitrogen-fixation capabilities and light canopy, encourages the grass growth beneath, and because of its mono-dominance, was prone to periodic dieback and re-sprouting from locust borer outbreaks (Fig. 1) (Wade, 1994; Groninger *et al.*, 2007).

More recent studies have shown that forest top soil can be used (Holl, 2002). This can be carefully set aside prior to mining or taken from appropriate sites that are not contaminated with invasives. The soil should be laid back on the subsurface without careful landscaping, by arranging the soil loosely without any grading. The roots and the buried seed bank of herbs (raspberries, blackberries) within the soil will germinate. Wind-dispersed seed of both annual and perennial herbs will also quickly colonize the exposed surface and take hold within the microtopography of the ungraded loose soil. Wind- or bird-dispersed fast-growing pioneers of the initiation stage of stand development (e.g., bigtooth aspen, red maple, black locust, Virginia pine, birch) can quickly succeed the herbs. If dispersal is patchy, planting can be done, particularly of slower-growing, poorly dispersed late-successional species (e.g., oaks, hickories). Sometimes these can be planted beneath the pioneers using a relay floristic model on the more sensitive and exposed sites, or an initial floristics model can integrate plantings of both pioneers and late-successional species (Groninger *et al.*, 2007). After about 15–20 years, canopy closure occurs, excluding the groundstory herbs and grasses from the site, and fostering an understory of shade-tolerant herbs and shrubs that can come in over time or through deliberate underplanting (Fig. 2).

Box 25.5 Figure 1 An arrested grassland mine reclamation site with resprouting black locust. *Source:* M. Hiscar, 2006, in Groninger *et al.*, 2007. Reproduced with permission from ARRI.

Box 25.5 (Continued)

Box 25.5 Figure 2 A 47-year-old stand of second-growth forest that established naturally beneath pine and black locust that was planted on loose soil with no groundcover, on a reclaimed mine site in Eastern Tennessee. Yellow-poplar dominates the emergent stratum with red maple and northern red oak in the canopy and mid-story. The hardwood regeneration came from an adjacent native forest. *Source:* V. Davis in Groninger *et al*., 2007. Reproduced with permission from ARRI.

Box 25.6 Landfill reclamation: examples from the lowlands of Puget Sound, Seattle, and the Fresh Kills Landfill, New York.

Large parts of the urban environment are degraded. They range from roadsides and streets, to parks, industrial brownfields, and abandoned house lots. Each kind of use has a differing degree and kind of degradation and a different approach toward its restoration. One area that requires a unique aspect of restoration is the landfill site. Sites across America have become dumping grounds for refuse for centuries. They are the oldest form of waste disposal as compared to incineration or resource recycling. They are often seen as cost effective but their disadvantages are numerous. They are often a significant source of leachate pollution to aquifers, streams, and water supplies, and a source of methane pollution from anaerobic decomposition of the waste, that is four times more powerful as a greenhouse gas than carbon dioxide. Surrounding property values are obviously lower, and if poorly managed, landfill sites can be a source of disease. There are over 850 landfills in the US that have active gas-recovery systems that create a source of energy rather than pollution. In addition, there are active programs to restore landfills so that they can be used as valuable areas for recreation, open space connectivity, and wildlife habitat.

Although there is an engineered protocol for encapsulating landfills to prevent leachate and pollutants from entering nearby water sources, as well as technologies that can capture gases for energy after their useful life has ended, the role of ecological restoration is somewhat rudimentary. Many landfills are sealed with clay to prevent rainfall from entering, and then are seeded to grasslands that are maintained to prevent succession and to prevent roots from woody plants developing and penetrating the seal. Thus, most capped landfills have a number of degradation problems that relate to the fact that the topsoil and subsoil sit on top of the capped clay layer. The topsoil is compact from the use of heavy machinery, with little organic matter, low micro-faunal activity, and poor structure. In a study in the lowlands of Puget Sound, Seattle, mounding had the greatest positive effect in encouraging successful establishment of herbaceous plants and grasses, more than mulches and fertilization (Ewing, 2002).

Forest succession can be encouraged around the fringes of landfills. One such example is the Fresh Kills landfill on Staten Island, New York (Fig. 1). The landfill has been capped, the topsoil restored and stabilized, but succession

(*Continued*)

Box 25.6 (Continued)

has failed to develop around the margins, primarily because of an absence of viable dispersed seed. Handel and colleagues planted 17 species of native trees adapted to coastal northeastern habitats (Robinson and Handel, 1993). The planted shrubs and trees served to attract birds, even though most of the plants were not reproductively mature. Overall, an additional 20 new tree and shrub species established beneath and around the plantation, 71% of which were fleshy berry species dispersed by birds and 20% were wind-dispersed. Taller trees served as an attractant to birds and were more effective at serving to establish natural regeneration. The nucleation strategy of planting islands of trees and shrubs is therefore an effective mechanism to jump-start succession (Fig. 2).

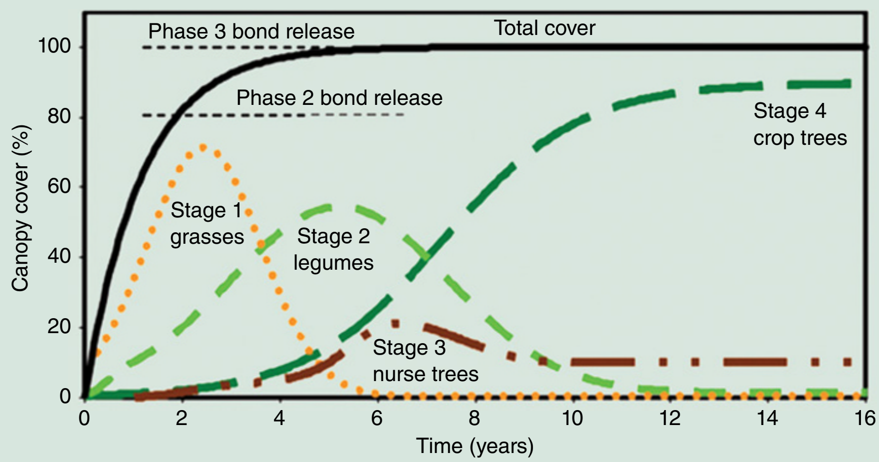
Box 25.6 Figure 1 An aerial photograph of the Fresh Kills Landfill as seen in 2014. *Source:* James Corner Field Operations. Reproduced with permission from the City of New York.

Box 25.6 Figure 2 A schematic sketch of what a future restored woodland around the margins of the Fresh Kills Landfill would look like in 2030, with open grassland and shrubs on the cap with trails and bikeways. *Source:* James Corner Field Operations. Reproduced with permission from the City of New York.

Box 25.7 Using ground covers that are compatible with forest restoration.

Many groundcovers are used to successfully smother competition and inhibit succession. Such covers are commonly done in agroforestry systems that can be classified as permanent (see Chapter 29). An example of using compatible ground covers that initially colonize bare open sites is recommended for Appalachian mine reclamation (Burger *et al.*, 2009). These groundcovers allow more light to penetrate to the ground surface and take up nutrients and soil water more conservatively than traditional fast-growing groundcovers (usually nitrogen-fixing legumes, e.g., *Pueararia* spp.). This makes growing space available to volunteer tree seeds that have been dispersed by wind or birds (Fig. 1). In areas where invasive exotic species are not dominant components of the vegetation, this can work very effectively, but in urban areas or agricultural areas that are disturbed and dominated or arrested by invasives, this technique might not be successful.

For mine reclamation, four stages are recognized. Stage 1 is where bunch grasses are seeded within a fertilizer mulch, and dominate with the first year of establishment. The openings among the grasses provide growing space for the establishment of pioneer tree regeneration. Stage 2 starts the second year when more perennial legumes and other native herbs start to dominate the site. These plants are eventually shaded out by the volunteer or planted trees but function to fix nitrogen and stabilize the soil. Stage 3 occurs generally within 5 years, when the pioneer trees and shrubs start to cover the area. Many bird-dispersed trees and shrubs attract more seed-dispersing animals when they mature, promoting greater numbers of regenerating species. Stage 4 is when the later successional species start to dominate the canopy and leaf litter starts to accumulate on the forest floor.



Box 25.7 Figure 1 The four stages of dominance using successional groundcovers compatible with tree establishment. *Source:* Burger *et al.*, 2009. Reproduced with permission from ARRI.

Box 25.8 Mangrove restoration in Indonesia, Thailand, and Vietnam.

Although mangroves represent a small area relative to other forest types, they are of global significance because they provide people and societies with critical ecosystem services. These services include buffering and coastal protection from storms, critical nursery habitat and protection for fish, shrimp, and other crustaceans, and important nesting habitat for colonial seabirds (Figs. 1, 2). They are also important nutrient and carbon sinks from sediment-laden tidal and riverine waters that are physically slowed by mangrove roots. Obviously people also depend on mangroves for seafood and as a source of firewood.

Mangroves across the world are under threat of destruction and degradation (Fig. 3). Sea level rise predicted to be over 3 ft (1 m) will inundate and completely alter tidal flux, and thus their establishment floristics. Over-cutting for charcoal has degraded, and in some places, completely eliminated mangroves. Mangroves have also been destroyed to create shrimp farm ponds. All of this is predicted to increase flooding, coastal erosion, and salinization. Estimates from some studies suggest that about 20–30% of mangroves worldwide have disappeared (Millennium Ecosystem Assessment, 2005).

The most common mode of restoration is simply to plant seedlings on denuded mud flats where the mangroves used to be (Fig. 4). If the nature of the hydrology and tidal system has not dramatically changed, then this can work, particularly if the only missing component is a seed source and its effective dispersal. Otherwise, if a seed source is available

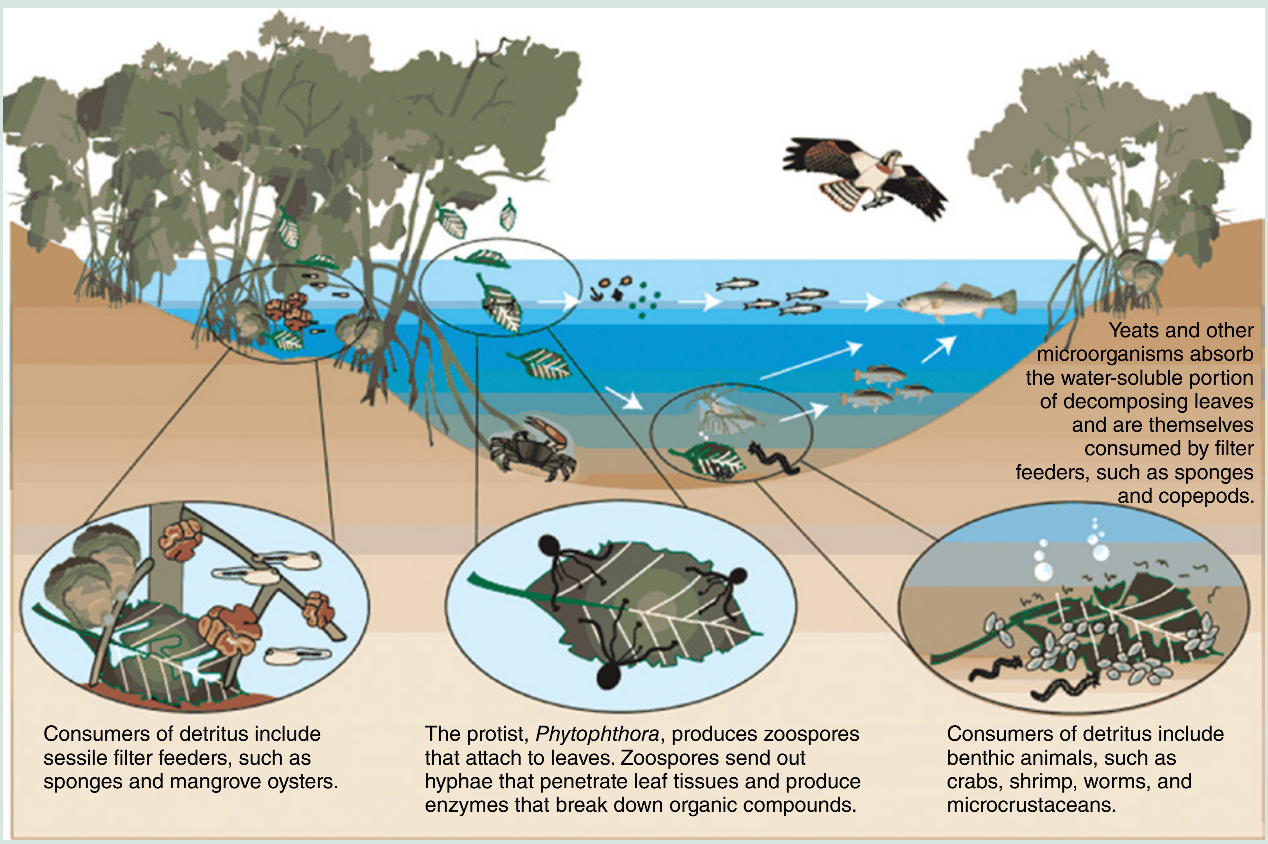
(*Continued*)

Box 25.8 (Continued)

and dispersed, all that is needed is site protection. However, in most circumstances this ends in failure because the tidal flux has changed because of drainage, blockage from dams, or because the deforestation has inextricably altered the system. It is therefore critical to assess the nature of the degradation process first, before resolving and developing a restoration pathway. The Ecological Mangrove Restoration method suggests the following (Lewis, 2005).

1) Assess the autecology of the tree species and mangrove forest type and their reproductive ecology.
2) Create a digital elevation map and determine the nature of tidal flux and hydrological flow to determine where seedlings should and can establish.
3) Identify what changes have degraded the mangrove and prevent it from reestablishing. If deforestation has not changed the functional integrity of the hydrology, then develop a structural restoration plan that mainly relies on protecting the site and working with the natural dispersal of propagules for regeneration.
4) If the hydrology has significantly changed, develop a functional restoration plan to resolve any drainage or damming and to recover the original tidal and hydrological flows, and implement the plan.
5) Protect the site from human influences, and monitor patterns and nature of natural regeneration establishment.
6) If natural regeneration is slow or failing, then devise a planting program with the right species selection and planting site.

There will be some areas where mangroves have been completely denuded and soil erosion has progressed to an extent that restoration has moved beyond simple corrections in the hydrology, but required physical changes to rebuild the soils and the hydrology. Soils that have become salinized and toxic, low in oxygen, and so severely eroded, have to be restored incrementally through a relay floristic model using species adapted to such conditions first before reintroduction of native mangroves.



Box 25.8 Figure 1 A representative diagram of a mangrove in Florida. *Source:* Kruczynski and Fletcher, 2012. Reproduced with permission from IAN Press.

Box 25.8 (Continued)

(a)

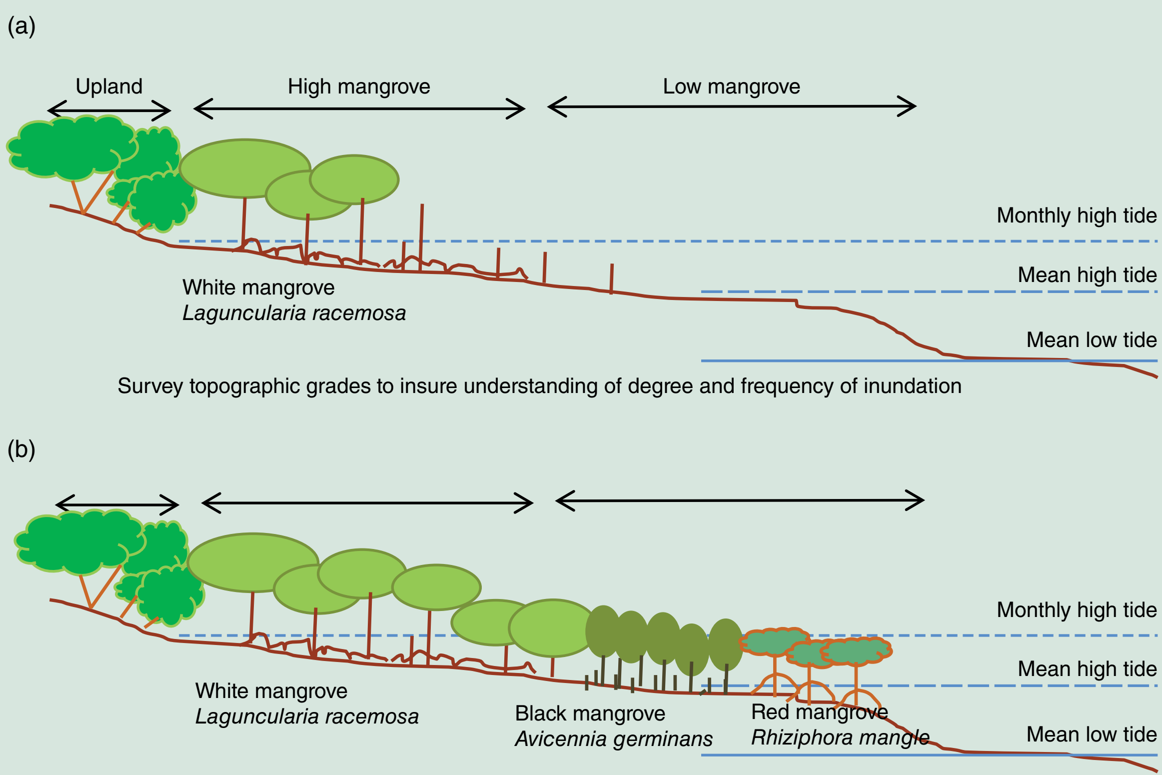
(b)

Box 25.8 Figure 2 (a) An aerial view of a mangrove estuary ecosystem on the gulf coast of Thailand. *Source:* W. Meepol, Ranong Mangrove Forest Research Center, Thailand. Reproduced with permission from W. Meepol. **(b)** An intact and healthy red mangrove stand on the outer zone of a tidal river, Thailand. *Source:* J. Bukoski. Reproduced with permission from J. Bukoski.

(*Continued*)

Box 25.8 (Continued)

Box 25.8 Figure 3 An example of mangrove degradation where human-altered tidal flux increased salinity and inundation. The red mangroves in the foreground are dead while some of the black mangroves survive behind. *Source:* J. Bukoski. Reproduced with permission from J. Bukoski.



Box 25.8 Figure 4 An example of a mangrove restoration plan that recreates the natural zonation of species in relation to tidal influence and degree of salinity. **(a)** Deforestation in the red and black forest mangrove zones. **(b)** A reforestation plan. *Source:* **(a, b)** Mark S. Ashton.

Summary

To summarize this chapter, understanding the manner and the degree to which forest degradation has occurred is the first step toward taking action, if so desired. The second component is then understanding what kind of action is necessary. Restoration can take multiple pathways that are defined by the ecological constraints of what is possible, and the social drivers of how far and for what purpose restoration, including reclamation and rehabilitation, is desired (Table 25.1).

Table 25.1 Summary of degradation effects and restoration choices progressing from less intensive to more intensive degradation phenomena and associated restoration treatments.

Intensity of degradation impact to forest

Intensity of restoration treatment

Degradation phenomenon	Examples of silvicultural restoration techniques
Chronic vegetative degradation	**Rehabilitation strategies**
Top-down: sequential and repeated loss of structure and composition affecting the forest canopy. Examples: selective logging and diameter-limit cutting	1) Enrichment planting of late-successional canopy dominant trees with release treatments, e.g., cleaning, liberation (relay floristics) 2) Cut all the vegetation back to the ground and facilitate release of natural regeneration of late-successional tree species with pioneers (initial floristics)
Bottom-up: sequential and repeated loss of forest structure and composition at the groundstory. Examples: overgrazing, weeding and cultivation of groundstory, burning, grazing	1) Enrichment planting understory tree and shrub species with protection from degradation factor (grazing, cultivation) 2) Facilitate reinitiation of understory tree and shrub species through natural regeneration with protection from degradation factor
Acute vegetative degradation	**Rehabilitation strategies**
Sub-lethal: incomplete land clearance that does not destroy sprouts, roots, and subsequent recruitment of pioneers. Examples: swidden and smallholder agriculture	1) Protect and release regeneration after agricultural/pasture abandonment, e.g., old-field succession (relay or initial floristics) 2) Enrichment plant late-successional canopy dominant trees with release cleanings within old-field succession if absent from site
Lethal: complete or extensive clearance of land for permanent cultivation of agricultural crop. Often such sites cannot be sustained and converted to fire- dependent fern or grassland. Examples: industrial agriculture and ranching	1) Plant exotic tree species, if native trees are maladapted to open sites, to shade out grasses/ferns and allow native species to recruit beneath or enrichment plant (relay floristics) 2) If seed dispersal inadequate, establish native long-lived pioneers in mixed plantations (initial floristics) 3) Plant long-lived and short-lived pioneers that draw seed dispersers in groups to facilitate nucleation (relay floristics)
Acute physiochemical degradation	**Reclamation strategies**
Lethal: complete/extensive clearance of land and change in hydrology, soil structure and fertility. Examples: surface mining, gravel pits, agricultural sheet erosion, landfill reclamation	Two-step process: (1) soil stabilization by physical contouring and terracing, restoration of topsoil, addition of organic mulches and site protection by ground covers; (2) establish plantations of exotic and/or native pioneers; facilitation of succession through nucleation; or, if adequate seed dispersal, promote tree establishment through natural regeneration and succession

Source: Mark S. Ashton.

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26

Approaches to and Treatments for Maintaining Healthy Forest Ecosystems

Introduction

There are many definitions of forest health ranging from the narrowly defined aspects of utilitarian use to purely ecosystem perspectives. With traditional thinking, insects and diseases are considered to be detrimental to a forest. The utilitarian perspective may be appropriate for the production of products from single intensively managed tree crops (see Chapter 30) but for many other kinds of multiple-purpose management, this is inappropriate. Many management goals that take on a more inclusive perspective of managing forests have the intention of retaining their complexity by including all species and their legacies (snags, woody debris) in management regimes (see Chapter 28).

Irrespective of concerns about an ecological focus to management, forest health should be considered from an anthropocentric perspective. It is almost impossible not to think otherwise. Interests around forest health center on concerns about invasives, pathogens, and insects, and there is a tendency to focus on those that are creating the most impact on the utilization of timber and non-timber forest products, aesthetics and use in urban environments, and perceived damage to wildland ecosystems. Thus, it is not surprising that the amount of research on forest health has been dramatically biased in favor of trees and plants of perceived economic and social importance. The most accepted definition of forest health that will be used in this book is one in which forests are managed to sustain their complexity while providing for human needs. Healthy forests are able to recover after being stressed (Edmonds, Agee, and Gara, 2000). They are able to bounce back after impacts that reduce their primary productivity, loss of nutrients, degraded structure, and/or widespread influence and severity of insects and pathogens. Currently, courses are taught that integrate all aspects of forest protection and health using an ecological framework for diagnosis and control. But not too long ago, the many facets of forest health were dealt with in separate academic courses in fire (Pyne, Andrews, and Laven, 1996), pathology (Manion, 1991; Tainter and Baker, 1996), and entomology (Coulson and Witter, 1984; Speight and Wainhouse, 1989; Waring and O'Hara, 2005). Today there are now several more subjects that must be included within forest health that are perhaps more important than all others: the subject areas concerning invasives, air pollutants (e.g. ozone, nitrates), and climate change.

This chapter starts with background sections on the growing influence of non-native invasives followed by a description of a conceptual approach to incorporating forest health into the stand-dynamics paradigm. The core parts of the chapter can be divided into two parts: (1) protection against biotic agencies (e.g. insects, diseases); and (2) protection against abiotic agencies (e.g. ozone, acid rain, climate change). The chapter concludes with a section on using silviculture to control damage.

The Growing Threat of Non-Native Invasive Insects and Disease

In a global review by Kenis *et al*. (2008) of the 403 primary research papers published between 1900 and 2007 that concern invasive insects and pathogens, nearly two-thirds were published in the last 10 years (1997–2007); and two-thirds of all papers were focused on North America. By far the largest impact and focus on this subject has been on eastern North American landscapes and forests. The literature is also disproportionately focused on certain economically important taxa: two ant species account for 18% and 14% of the papers; the European honeybee accounts for 7%; the European gypsy moth accounts for 6%; and the adelgids, *Adelges piceae* and *Adelges tsugae*, account for 5% each (e.g., Smith and Nicholas 2000; Jenkins, 2003; Weckel *et al*., 2006). Since 2007 other important invasives to impact forests in eastern North America are the Asian long-horned beetle and the emerald ash borer. In a review by Marbuah, Green and McKie (2014) of the economic costs of harmful invasive

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

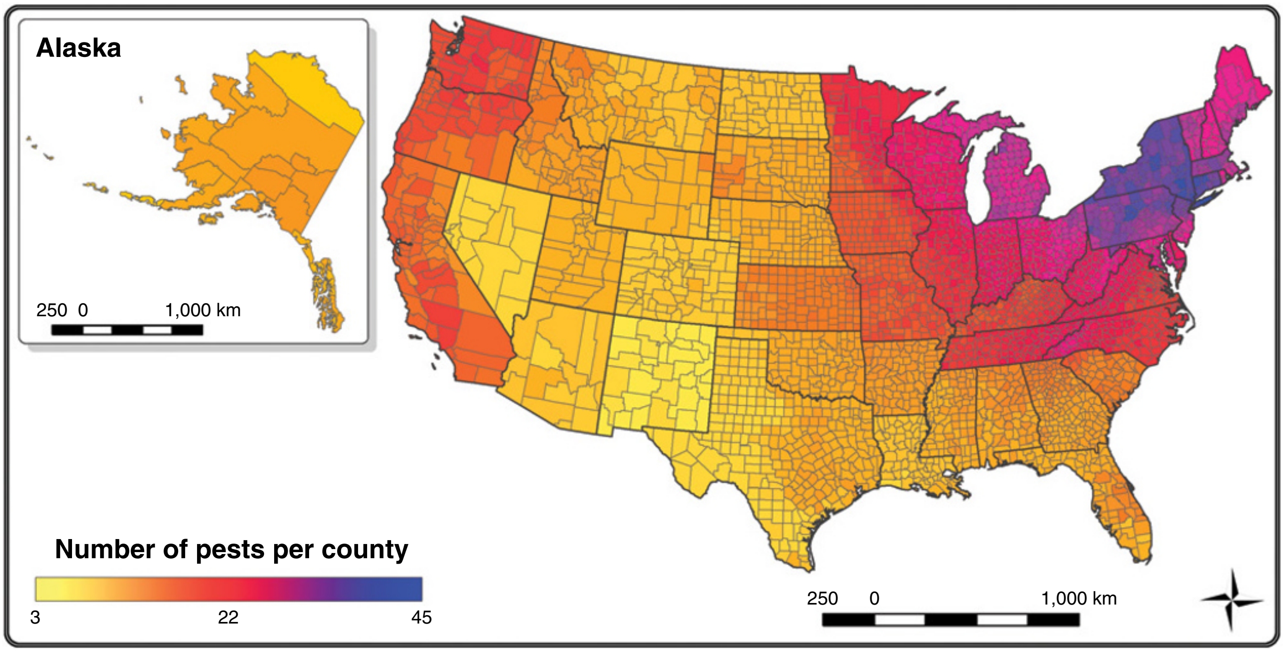

Figure 26.1 Numbers of damaging forest pests by county. *Source:* Liebhold *et al*., 2013. Reproduced with permission from John Wiley & Sons.

species to the economies of different countries, the US had by far the greatest impact with a cost of about \$185 billion dollars or 1.4% of GDP. Other countries that were severely affected included India at \$117 billion dollars and 12% GDP, and Brazil at \$45 billion dollars and 4.5% GDP. European countries faired better ranging from \$1–15 billion dollars or from 0.01–0.4% of GDP. Reasons for these differences are speculative but are probably related to a disproportionate amount of work on invasive impacts in North America as compared to other regions, and its relatively pristine native flora that is potentially more susceptible to invasives compared to Eurasia. The northeast has received by far the most impact of invasive species, given its long history of colonization and industrialization, and its large trade ports around the New York City area and the Great Lakes region (Fig. 26.1).

Steps to Control Damaging Impacts to Forests

It is important to recognize that, barring the effects of certain non-native invasives, most native damaging agencies and their impacts are as much a part of forest ecosystems as the trees themselves. It is better to learn how to live with and manage the sources of damage and disturbance impacts, than to attempt the impossible task of eliminating them. In many cases, this must include invasives, non-native diseases, and insects that can now never be eliminated given their widespread naturalization. The best approach to manage for forest health and reducing risk of invasives, insects, and disease involves combinations of tactics that come in steps. The first step involves building the health of stands and their resistance to disturbance and impact from "outside" agencies such as disease, insects, invasives, pollutants, and changes in climate. Ecological evidence would suggest that this can be achieved by creating greater structural, age-class, and compositional diversity at a scale appropriate to the long-term regional drivers of natural disturbance regimes (Franklin *et al*., 2002; Ellison *et al*., 2005; Waring and O'Hara, 2005; Stanturf, Palik, and Dumroese, 2014; Thomas *et al*., 2014; see Chapters 3, 4, and 5 for defining stand and landscape scale of management). But, as described later in this chapter, there is surprisingly little actual experimental work that has strongly supported the ecology, and what studies do exist are specific to particular taxa (e.g., bark beetles), with studies on other taxa (e.g., defoliators) showing no relationship or contradicting current thinking. Clearly, much more work needs to be done to determine the complex interactions among host plants, their damaging insects and pathogens, and in turn the parisitoids and predators of the insects and pathogens.

Any feasible measures to prevent impacts on the forest before they occur need to come next. Examples of prevention include controlling for, and excluding, exotic insects and diseases at a country's ports, reducing and

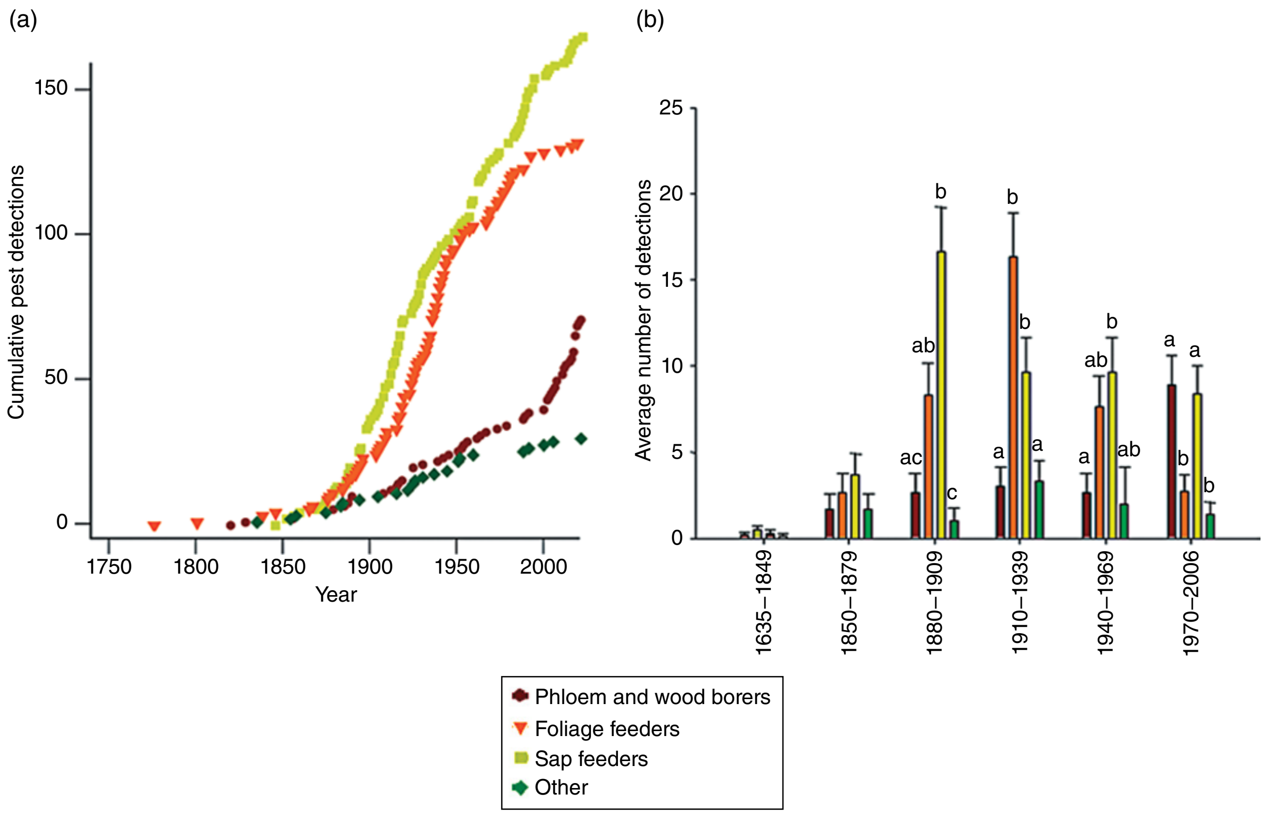

Figure 26.2 **(a)** Cumulative detections of non-native forest insects by functional group over time. Note the declining increases in cumulative detections of foliage feeders and sap feeders but the exponential increase associated with phloem and wood borers. **(b)** The average count per 10-year period with approximate standard errors versus the six time intervals by functional guild. Different letters indicate significant differences in detections between guilds at that time-period based on pair-wise comparisons per period. *Source:* **(a, b)** Aukema *et al.*, 2010. Reproduced with permission from Oxford University Press.

controlling air pollution emissions, and controlling access to forests via roads and trails where humans, vehicles, and equipment can act as conduits for invasive plants, disease, and insects. Humans can also directly affect the forest itself by illegal activities, such as hunting, exploiting valuable timbers and non-timber products, or converting land for other uses. Many of these impacts reflect greater social and ecological issues that are far beyond the control of the forester who is concerned with the stand or forest under scrutiny, and require better national and international policies, laws, and governance. For example, regulations that enforced the control and careful screening of importation of horticultural plants in the early 1900s strongly curtailed the invasion of many damaging defoliators and sap suckers that came into the US with imported plants (Fig. 26.2). However, the exponential increase in trade has increased all other forms of insects and diseases, particularly those wood-boring insects associated with wood packaging, even with some degree of inspection (Fig. 26.2b). At the stand-level and forest-level, the forester can control the impacts of damaging agencies by having readily accessible roads that are well protected and controlled, and that provide good access for fire suppression, routine monitoring and surveillance, quick and timely application of pesticides or biocontrol, timely salvage, prescribed burning, and those kinds of partial cuttings that improve the vigor or health of stands.

If and when an actual impact occurs and has become established, combative treatments may need to be applied to suppress the effects of damage. Finally, dead or damaged trees can be salvaged when all else has failed. These steps can be summarized as a conceptual approach for protecting intact forested stands (Box 26.1) but unfortunately this is not the usual case. In most circumstances, foresters are faced with forests and stands that have had a history of impact and degradation from a damaging agency, either direct or indirect. In these cases, stands need to be "restored" to some greater functional and more productive state than their current form (see Chapter 25 on degradation processes and restoration treatments).

Box 26.1 A conceptual approach to protecting forests.

Step 1: Ensure Health and Resistance of Stands

Build the health of stands and their resistance to disturbance and impact from "outside" damaging agencies by creating greater structural age-class and compositional diversity at a scale appropriate to the long-term regional drivers of natural disturbance regimes.

Step 2: Prevent Impacts to the Forest

Take feasible measures to prevent impacts to the forest before they occur by multiple means. Two scales of prevention should occur. At the scale "beyond the forest," this includes controlling access to forests, controlling air pollution, and preventing pests and pathogens from entering through trade or travel. At the scale "within the forest," immediately control an outbreak by ensuring good access throughout the forest for routine monitoring, use of pesticides or bio-control, or fire suppression.

Step 3: Use Combative Treatments

When the actual impact occurs and is beyond immediate control, take combative treatments to suppress the effects of damage through sanitation cuttings and by encouraging the more vigorous trees through thinnings.

Step 4: Salvage

Finally, salvage dead or damaged trees when all else has failed.

The Concept of Forest Ecosystem Health within Stand Dynamics

Given that the concept of forest health has a strong anthropocentric perspective, it is also not surprising that much of the literature demonstrates that human-dominated forest ecosystems have become very dysfunctional with continuous chronic impacts of invasive diseases, insects, plants, and animals; chemical pollutants from agriculture, industrial manufacturing, and energy emissions; and the accumulated phenomenon of climate change (Box 26.2). This also means that forest ecosystem health is influenced as much at regional scales that relate to social and economic issues of governance (watersheds, basins, and landscapes) as they are at the stand-level scale of the forester's domain. However, at smaller scales, forest ecosystem health can also be potentially assessed using the stand-dynamics paradigm.

Three attributes can be used within stand dynamics to gauge forest health: **vigor and vitality**, **resilience**, and **organization**. Rates of growth and crown (leaf) area can be used to gauge vigor that is referenced to the limitations

Box 26.2 The legacy of past land-use and cutting history as a stage for insects and disease.

Past management and land-use history have promoted single-species dominance in many circumstances across North America, making forests more susceptible to insects and diseases. For example, in eastern North America, colonization, clearance of native mixed forests for agriculture and then subsequent abandonment of much of the marginal uplands, led to even-aged mono-dominant stands of "old-field" conifers that differed in species by latitude (e.g., white spruce in maritime Canada; eastern white pine in New England; eastern redcedar in New York and New England; Virginia pine in the Mid-Atlantic; loblolly–shortleaf pine in the Piedmont; loblolly–longleaf in the Gulf and coastal plains; slash–sand pine in Florida). Subsequently, these new mono-dominant forests were cut for timber, beneath which, in many circumstances, even-aged second-growth stands of hardwood were released. In the southern US, many of these "old-field" conifers were converted to even simpler single-species plantations of loblolly and slash pine. Insects and diseases that followed this series of forest transitions can be equated to the lop-sided age-class distribution and to species mono-dominance. For example, white pine blister rust and the weevil were prevalent with old-field white pine, chestnut blight and gypsy moth were prevalent at the time of second-growth chestnut and oak dominance respectively, and southern pine beetle can reach epidemic proportions in southern pine plantations.

The history of forest cutting is another mode of human impact on forests that leads to forest simplification. Examples of this in the eastern US are spruce budworm and its predominance in heavily cutover, even-aged balsam fir forests of Maine and eastern Canada, and the tent caterpillar outbreaks in cutover aspen forests of the northern hardwood–spruce–fir region of the north-central US and Canada. In the same region, the absence of fire on infertile soils has promoted the recruitment of oak on sites originally dominated by red pine, making the oak prone to dieback and gypsy moth defoliation. Similarly in the western US, a heavy cutting history in concert with protection from fire has promoted even-aged, mono-dominance of more shade-tolerant, but drought-prone, conifers over shade-intolerant, drought-tolerant conifers. Recent prolonged droughts of the last 30 years have stressed many of these forests making them susceptible to epidemic bark beetle infestations in tandem with catastrophic wildfires.

of site (e.g., soil fertility). Resilience can be measured in a stand's ability to maintain its structure and composition in the presence of a stressing agent, either biotic (e.g., insect, disease) or abiotic (e.g., pollutants, wind, ice). An example of resilience at the species level is a plant that can respond to different kinds of disturbances by a variety of regeneration modes (e.g., sprouting, wind-dispersed seed, advance regeneration) or to a variety of protective strategies from herbivory (e.g., spines, leaf toughness, phenols, and tannins). Plants and forests that do not have a diverse array of regeneration mechanisms or protective mechanisms would be considered less resilient to varied disturbances or different kinds of herbivory. **Redundancy** is a form of resilience. An example of redundancy is when multiple species have the same set of adaptations and mode of regeneration. If any one species in this group succumbs to a pathogen or insect, the remaining species perform the same functional and successional role within a stand's development. The third attribute to measure is organization. Measures of organization include the number of trophic levels of the food web and the number of interactions between trophic levels.

North American forests are faced with a deluge of impacts affecting their health. In the west, the main impacts include suppression of natural fires, and droughts that interact with fires and fire suppression to promote huge episodic outbreaks of root diseases, bark beetle infestations, and insect defoliation (Allen *et al*., 2010). In the east by far the greatest impact is from wave upon wave of invasive exotic pathogens and insects that are gradually taking out tree species of the eastern hardwood forests. All of these impacts may be exacerbated by climate change and air pollutants. It does not help to speculate that landscapes that have been simplified from more complex species mixtures and age classes to large homogeneous single-species and single-aged stands are more susceptible to insect and disease outbreaks. The US Forest Service has a National Forest Health Monitoring Network that serves to detect insect and disease outbreaks across the nation's forests. Early detection can provide a strategic advantage in first evaluating the problem area and then controlling the outbreak if necessary. When a problem requires control, two forms of protective action can be defined: protection against biotic agencies (insects and disease); or protection against abiotic agencies (climate change, fire, drought, pollutants).

Protection Against Biotic Agencies: Insects and Disease

Consideration of biotic enemies best starts from recognition of the fact that the trees of any kind of forest represent a source of food to a wide variety of organisms (Table 26.1). Owing to the availability of food, organisms ranging from minute viruses to large herbivorous mammals have evolved that are adapted to feed on plants. These organisms are so dependent on the vegetation that changes in the forest will cause changes in the populations of dependent organisms. This would be defined as a bottom-up driver (Schmitz, 2005). There are examples of the other way around, where herbivores can change the vegetation by their own behaviors, usually in response to the kind of predator that they are exposed to (Schmitz, 2005). This would be defined as a top-down influence. It is important to understand which processes are driving change.

Fortunately, only a very few of the dependent organisms are harmful. In a sense, the organism that kills its host, and thus its supply of food, is a poorly adapted one. This is why introduced organisms (animals, plants, insects, and diseases) often cause much more ecological impact and economic loss than the native ones. Well-adapted damaging organisms sometimes cause so little damage that they go almost unnoticed. However, some of these cause substantial economic damage without threatening the life of the tree. For example, the heart-rots that attack the non-living wood inside a tree can ruin the utilizable wood without significantly harming the vital processes of the tree. The need for modifying silvicultural systems to reduce losses to biotic enemies can normally be confined to those few organisms that can cause serious loss. The vast majority that merely feed on the trees without important damage do not require control measures.

Direct control of damaging organisms (i.e., insects, disease, invasive plants) involves attacking the insects or pathogens themselves either with pesticides or with various methods known as **biological control**. Biological control involves the introduction or encouragement of biotic agencies that combat the damaging organisms. Suitable agents include fungi that are antagonistic to damaging ones, parasites of insects, or predators of herbivores. **Indirect control** refers to measures that make the circumstances less favorable to the damaging organism or more favorable to their hosts. This consists mostly of silvicultural treatments that can create the forests and forest environments that resist either damaging agencies or the effects of damage by them. These distinctions are not necessarily perfect; for example, silvicultural measures can be used to encourage the biotic enemies of insects or to eliminate trees that are sources of pathogen infection.

It must be recognized that such treatments are seldom completely successful, and that a good outcome at one time and place does not guarantee similar results elsewhere. Such programs, like so many things in silviculture, are best regarded as the continuous application of adaptive management. Successful silvicultural treatments that account for damaging organisms to the trees usually involve several kinds of measures, and are tailored to each complex biological situation, so that it is difficult to fit them into any simple category. Thus, it is important to

Table 26.1 Forest insects and diseases that have severely impacted North America's forests, subdivided by their origin (introduced or native), region (eastern or western North America), and by type (insects or pathogens).

Agent	Common name	Origin	Nature of attack	Host
Eastern North America				
Insects				
Adelges piceae	Balsam wooly adelgid	Invasive (Europe)	Sap/phloem	Balsam fir
Adelges tsugae	Hemlock wooly adelgid	Invasive (Asia)	Sap/phloem	Eastern hemlock
Agrilus planipennis	Emerald ash borer	Invasive (Asia)	Cambium	Ash
Choristoneura fumiferana	Spruce budworm	Native	Defoliator	Balsam fir
Dendroctonus frontalis	Southern pine beetle	Native	Cambium/xylem	Southern pine
Lambdina fiscellaria	Hemlock looper	Native	Defoliator	Hemlock, fir, spruce
Lymnatria dispar	Gypsy moth	Invasive (Eurasia)	Defoliator	Hardwoods
Operopthera brumata	Winter moth	Invasive (Europe)	Defoliator	Hardwoods
Diseases				
Cryphonectria parasitica	Chestnut blight	Invasive (Asia)	Cambium/phloem	Chestnut
Cronartium fusiforme	Fusiform rust	Native	Cambium/stem	Southern pines
Cronartium ribicola	White pine blister rust	Invasive (Eurasia)	Needles/stem	White pine
Discula destructiva	Dogwood anthracnose	Unknown	Leaves/stem	Dogwoods
Nectaria coccinea	Beech bark disease	Invasive (Europe)	Bark/phloem	Beech
Ophiostoma ulmi	Dutch elm disease	Invasive (Eurasia)	Xylem/phloem	Elms
Phytophthora cinnamomii	Littleleaf disease	Native	Needles	Shortleaf pine
Western North America				
Insects				
Choristoneura occidentalis	Western spruce budworm	Native	Defoliator	Douglas-fir, firs, larch
Dendroctonus ponderosae	Mountain pine beetle	Native	Cambium/phloem	Pines
Dendroctonus brevicomis	Western pine beetle	Native	Cambium/phloem	Pines
Orgyia pseudotsugata	Douglas-fir tussock moth	Native	Defoliator	Douglas-fir
Diseases				
Arceuthobium spp.	Dwarf mistletoe	Native	Stems and foliage	Conifers
Armillaria spp.	Armillaria rot disease	Native	Roots	Conifers
Phellinus weirii	Laminated root rot	Native	Roots	Douglas-fir, firs, hemlock
Phytophthora ramorum	Sudden oak death	Invasive	Stems	Oaks, rhododendrons

Source: Mark S. Ashton.

watch for syndromes of successive interdependent causes of damage or mortality. For example, a defoliator such as the gypsy moth weakens trees, then a drought year or a cold winter makes them weaker yet, and finally some root-rot or bark-boring insect kills them. If one step is omitted, the trees may not die. If someone sees only one step, there is risk that inappropriate action will be taken or that a counterproductive argument will ensue with those who see only another step.

If there is adequate knowledge of the situation, it may be possible, by silvicultural measures, to create forests that are resistant to damage. In dealing with this or any other matter relating to damaging agencies, it clarifies analysis to distinguish between **susceptibility to attack** and **vulnerability to damage**. For example, oak stands on very dry soils where the litter gets hot during the day, will become very susceptible to gypsy moth attack because the larvae do not descend to the ground where mice can feed on them during the day (Doane and McManus, 1981). However, the defoliated oaks on those soils are not as vulnerable to mortality because the root-rot fungus, *Armillaria mellea*, is not as prevalent as it is on more mesic sites. On the better soil, mice reduce the defoliation, but if the trees are defoliated, they are more vulnerable to being killed by the root-rot. This can make it appear that the gypsy moth problem is confined to the

better soils. The possibility that the insect might spread from the dry to the good is obscured by the fact that the female moths of the most common US strain do not fly. However, some small larvae are dispersed by wind on silken threads. Furthermore, the risk of defoliation on the mesic sites is heightened by the tendency of birds to leave these sites and flock to feed on the dry sites where caterpillars are more abundant. This explains why outbreaks can start on dry ridgetops and later develop on the mesic soils, even though the biotic movement between the sites is more of birds than of insects. This is one of many cases in which the development of appropriate control measures depends on detailed knowledge of the actions of the damaging agencies.

Most of the classic generalizations about the damaging biotic agencies of the forest are more nearly true than false, but they cannot be accepted as a basis for silvicultural procedure without being scrutinized for applicability in each instance. All of them can be considered to modify habitat such that it is unfavorable and diminishes susceptibility to the impact of the insect or disease. Among these generalizations or propositions are:

1) modification of the stocking level to promote vigorous fast-growing trees more resistant to insect or disease;
2) adjustment of species composition with the assumption that mixed-species stands are less susceptible to insects and disease than single-species stands;
3) adjustment of age-class and size-class distributions as multi-cohort stands are more resistant to insects and disease than even-aged stands;
4) avoiding off-site conditions for tree species.

All four propositions have some evidence to support their use. However, given the spotty nature of this evidence, well-designed, long-term studies are needed to evaluate all four silvicultural generalizations on controlling insect populations and diseases.

Reducing Stocking Levels to Encourage Vigorous Fast-Growing Trees

The supposition in this treatment is that vigorous, fast-growing trees with plenty of growing space are more resistant than less thrifty, slow-growing trees. Trees that are supplied with plenty of light and soil moisture are potentially less susceptible to secondary diseases and insects. This can be called the plant stress hypothesis.

The best examples of reducing susceptibility by decreased stocking, and increased vigor by thinnings, and other removals of old, damaged, or infested trees, are with bark beetles. Plantations and natural stands that show signs of stress in southern and western pine stands can be thinned to reduce damage by *Dendroctonus* bark beetles (Thatcher *et al.*, 1980; Sartwell and Stevens, 1975; Belanger, Hedden, and Lorio, 1993). In southern pine stands, judicious improvement cuttings focused on leaving the most vigorous trees can be done to preclude outbreaks of bark beetles (Nebeker *et al.*, 1985). With western conifer species that are seriously threatened by heart-rot, it is logical to terminate rotations before the trees become old and highly susceptible. In addition, particularly with the pines (e.g., ponderosa, lodgepole) it is well known that, like the southern pines, thinning is an effective treatment to increase the vigor of the residual trees and to make them more resilient to bark beetle infestations (Fettig *et al.*, 2007). However, the type of thinning conducted and the nature of slash disposal is critical. The treatments that are proposed are not necessarily similar to fuels-reduction treatments (e.g., mostly low thinning). For reducing susceptibility to bark beetle infestation, crown or dominant thinning that takes out the larger pine (dominant and codominant) and spaces the smaller pine is recommended. Slash disposal by chipping or by burning in piles is important to reduce attraction to pinewood. Low pine stocking densities also reduce beetle fecundity and overall fitness, and increase wind movement, air turbulence, and desiccation that disrupt beetle pheromone emissions and colonization (Bartos and Amman, 1989; Thistle *et al.*, 2004).

If prescribed fires are used instead of thinning treatments to more naturally thin pine stands, their variability and patchiness across the landscape can aid in creating a more heterogeneous species composition, age class, and stocking density that makes pine less susceptible to infestation, but only after bark beetle infestations peak in the short term, having utilized all the post-fire mortality of standing dead pine (Fettig and McKelvey, 2010; Stephens *et al.*, 2012). Such an approach may be useful for more remote and extensive landscapes in the western US, whereas thinning treatments in tandem with slash removal might be more appropriate near human habitation, timber production areas, campgrounds, or recreational areas.

However, treatments to increase tree vigor to reduce susceptibility to defoliators does not work. For example, a study that fertilized and watered a spruce stand promoted greater infestations of western spruce budworm (Clancy, Itami, and Huebner, 1993; Clancy, Wagner, and Reich, 1995), and stem rusts of conifers and the white pine weevil are more serious problems of vigorous trees than of the less thrifty. For defoliators, it is thus more important to promote their natural enemies, not to eliminate them, but to maintain their populations at low numbers. Birds are thought to be important predators of western spruce budworm, while rodents are thought to be important regulating controls for gypsy moth.

Adjustments to Species Composition and the Role of Mixtures

The assumption is that mixed stands are safer than pure, single-species, stands. This is partly based on many

studies, particularly in the tropics where tree diversity is high, that individuals of a species are less prone to insects and diseases when further away from their close relatives and siblings and surrounded by unrelated taxa that are not prone to the same insects and diseases. The term for this effect is negative density dependence (see Chapter 5).

In the majority of cases for temperate and boreal forests, mixed stands probably suffer about the same amount of damage from insects and pathogens as pure stands. For example, pure stands of spruce are much less susceptible to the spruce budworm than are mixtures of spruce with highly susceptible species such as balsam fir. In many other cases, however, mixed stands suffer less damage than pure ones. If the food supply of some insect does not include all of the species of a mixed stand, then it is diluted in ways that may inhibit buildup of the insect population. This is probably the chief advantage of mixed stands in insect and pathogen management. The physical separation of susceptible plants also inhibits the spread of many insects, especially those that disperse slowly or with difficulty. Fungi that spread through the soil, such as those causing most root rots, are often less common and less damaging in mixed stands. The long-term dispersal of insect pests of low mobility can be impeded by inedible plants. However, no real physical separation exists between species in a stratified mixture if there is an essentially pure stratum aboveground or belowground.

If a given mixture is more vigorous than pure stands, then it is more likely to be resistant to those insects that attack weakened trees. A mixture is probably more secure against insects than an uneven-aged pure stand because a given insect is more likely to attack many age classes of a single species than to attack different species.

Nevertheless, there are important instances in which pure stands are more resistant to certain damaging insects and pathogens than stands of the same species mixed with highly susceptible ones. Pure stands of spruce are more resistant to the misnamed spruce budworm than spruce–fir stands that have overmature balsam firs on which the insect can thrive. However, it may be noted that mixtures of hardwoods with spruce and fir are even more resistant.

The fact that the American chestnut grew in complex mixtures did not save it from the chestnut blight fungus. However, if it were still a major component in some eastern forests, there might be less difficulty with the gypsy moth, to which chestnut is unpalatable. The heteroecious stem rusts of conifers, or any other organism with alternate hosts, could not exist in absolutely pure stands. They are instead adaptations to the association of different species. The resistance of any kind of stand to its biotic enemies depends on the susceptibility to attack, and vulnerability to damage, of its individual components and not on doctrinaire generalizations. However, a mixed stand of both resistant and non-resistant species is bound to be more secure against injury than a pure stand of a non-resistant species, but less so than a pure stand of a resistant species. Sometimes the main value of mixed stands in this respect is the consolation that the risk of losing whole stands all at once is reduced.

The spruce budworm, one of the most dangerous insects of the North American spruce–fir forest (Sanders *et al.*, 1985), is an excellent example of an insect that is not merely a predator of the weak but also has a marked preference among species. The most typical form of this versatile insect is the scourge of the eastern portion of the spruce–fir forests, where massive outbreaks develop at intervals of several decades. It is poorly named because it is very dependent on and damaging to balsam fir. Spruces tend to be attacked when the supply of fir foliage has dwindled. The trees that are most susceptible to attack, but not extremely vulnerable to loss, are large balsam firs. These bear abundant staminate flower buds which are highly nutritious for young budworms. Susceptibility to attack is determined more by the proportion of mature balsam fir in whole forests than by the characteristics of individual trees or stands. It can be reduced to a limited extent by replacing large tracts of mature forests with an intermingled arrangement of stands in which the susceptible mature stands are diluted among younger and less susceptible stands. Vulnerability to the losses that are likely to occur after a stand is attacked can be somewhat reduced by pre-salvage of firs and spruces with poor live-crown ratios.

Adjustment of Age-Class and Size-Class Distributions to Diminish Susceptibility

The proposed treatments to diminish susceptibility include creating younger size- and age-class distributions with the assumption that smaller and younger trees are more vigorous. Regenerating stands can perhaps recalibrate species composition further, lessening susceptibility. The greater structural and age-class diversity is proposed to encourage more abundant numbers of parasitoids and predators of damaging insects in a similar manner to studies in agricultural systems (Stamps and Linit, 1998). However, studies in forests are very limited and contradictory. One study suggests reduced susceptibility with younger age classes for spruce budworm (Miller and Rusnock, 1993). In uneven-aged stands, there is ample opportunity for infection of young age classes from older trees by pathogens, such as dwarf mistletoe, that attack trees of all ages, thus enabling an infestation to remain established in a stand indefinitely (Fig. 26.3).

For eastern white pine, the main problem is usually the white pine weevil. This insect often kills the terminal

Figure 26.3 A forester in Montana examining a 25-year-old stand of lodgepole pine that has been infected with dwarf mistletoe from infected residual trees, such as the two taller ones in the center of the picture that had been left when the new stand was regenerated. *Source:* US Forest Service.

shoots of trees with tops in the sunshine. The replacement branches are usually the laterals of the previous year, and when they turn upward, they form crooks and forks that badly degrade the stems. One solution is to create more structural complexity through the use of the shelterwood method to keep the young trees partially shaded until at least one log-length has formed. Older white pines provide the best kind of shade because the weevils are lured away by their sunlit tops. The overstory must remain for such a long time that it should be composed of pines that can produce value rapidly and thus compensate for the slow growth of the deliberately stunted regeneration. The *Hypsipyla* borer, that damages the terminal shoots of mahogany and other members of the Meliaceae in the tropics, behaves in a similar manner.

The blister rust of the five-needled pines is also susceptible to some degree of silvicultural control by modification of stand structure. The spores that move from the alternate hosts, *Ribes* shrubs, cannot move over long distances and can germinate only on moist needle surfaces. Anything that forestalls the formation of dew on the foliage reduces the possibility of infection. This can be done by avoiding the creation of small gaps that are open to the sky and employing the sheltering effect of shelterwood cutting. Valley bottoms and areas close to large bodies of water are places where infection rates are high. In the case of western white pine and sugar pine, most losses result from infections of small trees, so preventing infection during the early stages is crucial. Eastern white pine trees can be infected at any height but are not as susceptible, so avoiding conditions suitable for dew formation usually suffices. In earlier years, much of the control effort centered on eradicating *Ribes*, but this approach proved expensive and not as effective as hoped. Sometimes the germination of stored *Ribes* seeds can be reduced by using shelterwood cutting and avoiding soil disturbance. The partial shade that is conducive to pine seedlings may be too much to allow the *Ribes* to survive and produce seeds. Recent evidence also suggests that rust-resistant natural populations may be built if rust-resistant parent trees are retained in the shelterwood seed source.

Avoiding Off-Site Conditions for Tree Species

By far the most important silvicultural approach to reducing losses to damaging agencies is simply the evasive action of avoiding conditions that are conducive to damage. It is remarkable how much damage from insects, pathogens, or non-biotic agencies can be traced to encouraging species or strains of those that are not

adapted to the sites or are simply exotics. Many root diseases are the result of attempts to grow a given species on soils that are too wet or too dry.

Less spectacular difficulties arise when a native or exotic species is planted, or is allowed to become established on a soil or site where it does not grow vigorously or does not grow in nature. The trees may develop well for some years and then fall victim to some insect or pathogen that may be acting simply as one of the factors that determines the natural range of the species. Some of the most common cases of this sort develop when some species or strain adapted to a moist site is grown on a dry one, but succumbs to a root disease or bark beetle attack after a drought year. This sort of difficulty can be reduced by timely thinning, but is better avoided altogether by not allowing the ill-chosen species or strain to grow there in the first place.

Exotics and Unnatural Conditions

Many, but not all, serious problems with insects and pathogens result from growing trees in habitats to which they are not adapted or from introducing exotic species of insects, pathogens, or their hosts. Introduced insects and pathogens are the most dangerous enemies of some species in almost every kind of forest (e.g., hemlock wooly adelgid, emerald ash borer, beech bark disease). Sometimes the only good way to control them is by judicious introduction of the enemies of the insects and pathogens that kept them in check in their native habitat. Introduced tree species that have left their natural enemies behind may flourish for a time and then suffer serious attack if their enemies catch up with them. They may also encounter serious difficulties with insects and pathogens native to the new habitat.

Other Aspects of Insect and Pathogen Management

Direct control with pesticides is far less important in forestry than in agriculture. It usually involves foliar applications of insecticides to combat defoliators, or applications to bark to control bark beetles. Sometimes the tendency is to regard insecticides as perfect solutions for forest insect problems and even to heap scorn on indirect control measures. There is also the highly popular view that all pesticide applications are at worst, dangerous, and at best, agents that merely prolong insect or pathogen outbreaks. The truth usually lies in the middle, but it is important to keep watch for the special cases in which extreme views are actually justified.

In forestry, insecticides and fungicides are commonly used on shade trees and in nurseries, where the hosts are very crowded and the crop is very valuable. It is very important to keep nursery seedlings from being infected with stem rusts, certain root rots, and other persistent disorders, because infected plants seldom recover after planting.

Efforts to develop resistant strains of forest planting stock by genetic manipulations have played a more important role in dealing with fungus diseases than with insects. Most of this effort has involved difficult problems with fungi, such as those causing stem rusts of conifers and the chestnut blight. Moderate success has been achieved in combatting the fusiform rust of loblolly pine and slash pine, as well as with some other diseases.

So many different kinds of modifications are aimed at reducing specific kinds of damage, that it is hard to detect any general or consistent way in which they conflict with other objectives. However, these measures usually complicate harvesting and other operations. The indirect silvicultural measures of control are often the slowest to take effect, but they are the most enduring and automatic (Knight and Heikkenen, 1980). Where indirect measures work, they can usually be depended upon to do so, even when no one remembers to do something at the right time.

Protection Against Abiotic Agencies

Pollutants

Acid rain, from nitrogen and sulfates, and ozone are pollutants in the air caused by various man-made emissions (Table 26.2). Ozone now has the most significant effects on North American forests (Fig. 26.4). Ozone in the lower atmosphere is formed largely from the reaction of sunlight on hydrocarbons that have been derived chiefly from burning fossil fuels. However, on hot days, phenols and terpenes are hydrocarbons emitted from the leaves of trees that can lead to increased ozone. Concentrations are extremely high in southern California and the Imperial Valley, around the urban areas of Dallas and Houston in Texas, and from the Great Lakes east to New York and New Jersey. As a pollutant, it can affect photosynthesis through leaf injury and chlorosis, particularly to stomatal openings. High areas of ozone concentration can dramatically reduce long-term growth rates in trees (Tkacz *et al.*, 2008). Ponderosa and Jeffrey pines are the most sensitive species to ozone pollution in southern California. Ozone impacts a wider array of trees species in eastern North America. There are no definitive numbers on the decline in growth from ozone on North American forests but it is believed to be significant.

Acid rain used to be a major pollutant to forests and water bodies, particularly in the northeastern United States. It is chiefly derived from emissions of sulfur dioxide, nitrogen oxides, and ammonia caused by the

Table 26.2 Abiotic pollutant stressors that have severely impacted North America's forests, predisposing them to insects and disease.

Pollutant	Nature of impact	Regions
Ozone	The most widespread pollutant In the west, ponderosa and Jeffrey pines are sensitive. In the east, studies have shown 30–50% declines in growth of most tree species during high ozone years	North America Hotspots: southern California, Atlantic coast, parts of the Great Lakes, southern Appalachians, north–central Pennsylvania
Nitrogen deposition	Nitrogen and ammonia deposition is highest in the east because of car exhaust across continental North America and prevailing winds carrying nitrogen pollution from west to east. Locally high deposition can be found in urbanized valleys and agricultural lands that use large amounts of fertilizer	Northeastern US; Central Valley, California; southern Idaho agricultural lands; Midwest: Ohio, Indiana
Acid rain	Sulfate pollutants from coal-burning power plants have been dramatically reduced since EPA regulations were passed	1960–1990s hotspots were in New England, Adirondacks, and the mid-Atlantic Appalachians. The areas affected are locally around the coal-fired power plants in Ohio and the Midwest
Greenhouse gases (carbon dioxide, methane)	Sources of gasses from burning fossil fuels, from forest land conversion and degradation, and from agriculture and livestock emissions Impacts vary by region, e.g., droughts, heatwaves, superstorms, floods, tornadoes, snowstorms, monsoons	Widespread changes in climate across North America with strong regional differences
Road salt	Local deposition on streets and roads. Surface runoff into riparian zones and roadside verges causing dieback and mortality	Urban and suburban areas affecting street trees in the snowbelt of North America

Source: Mark S. Ashton.

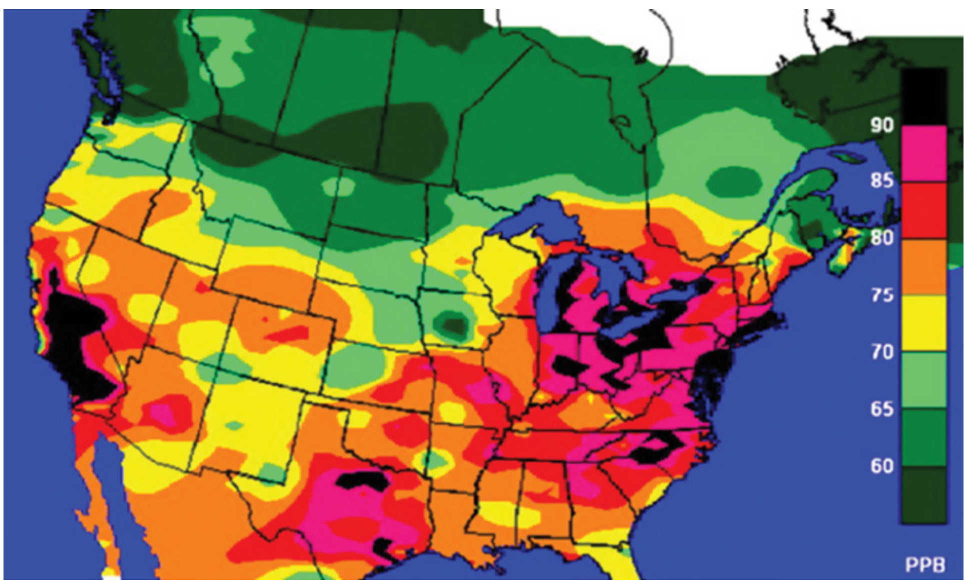

Figure 26.4 Spatial distribution of ozone at the ground surface across North America based on standard metrics averaged over a 3-year period (2001–2003). *Source:* Tkacz *et al*., 2008. Reproduced with permission from Elsevier.

combustion of fossil fuels. From 1900 to 1998 sulfur dioxide emissions increased from 9.9 million metric tons to a peak in 1974 of 28.8 million metric tons and then declined to 17.8 in 1998. Widespread dieback occurred in the most sensitive forests in the Appalachians, and they are now making a comeback after the Clean Air Act was passed in 1974, reducing sulfate emissions from coal-burning power plants, particularly in the Midwest, which were responsible for 60% of the emissions (Driscoll *et al*., 2001).

Nitrate pollution has increased dramatically, largely from vehicle emissions and fertilizer use in agriculture. In the western US, highest deposition rates are in the agricultural valleys of southeastern Idaho and southern California because of agriculture. In the eastern US, highest amounts are in the agricultural and coal-burning areas of the Midwest (IN, OH, MI, IL). However, the northeast receives nitrate/ammonium pollutants primarily from local vehicle emissions or emissions from the Midwest. Evidence suggests that nitrate deposition has acted as a fertilizer in young second-growth forests that have sequestered it in the vegetation and soils and prevented much of it from polluting waterways and drinking water supplies. This needs to be taken with caution because many of these same forests, particularly those on nutrient-poor soils (e.g. granitic base) such as in in Adirondacks (NY) and Maine, are very sensitive to acidification given their low soil buffering capacity, and with their maturation these forests are becoming more leaky. The forests of the Midwest are on much more nutrient-rich soils, and even though these forests receive much larger amounts of nitrate and sulfate, they have higher soil buffering (Driscoll *et al.*, 2001).

Fire

Forestry started in North America during a period when sporadic conflagrations had destroyed many sawmill towns with terrible loss of life in the Great Lakes region and the western US. These disasters were blamed almost entirely on accumulations of slash (Table 26.2). Laws were commonly passed, requiring that slash be burned in the vain hope that cutover land could be made fireproof. This view has persisted in the policy of some forest-fire control agencies and has been a major reason for the practice of clearcutting, broadcast burning, and planting. Sometimes slash disposal has become an end in itself, although extreme views favoring slash disposal collide with equally extreme opposition to any activity that generates smoke.

Forest fires spread chiefly through the dead, dry, leafy materials of the forest floor. Dead wood may be ignited by burning leafy materials but it is not the continuous fuel blanket through which fires spread. However, woody materials may burn hotly enough that embers from them may be wafted aloft and spread on the wind for substantial distances. They may spread across fire-control lines, and the woody materials themselves can impede the construction of such lines even if they are not burning.

Standing dead trees (snags) pose yet another dilemma for fire management. They are easily ignited by lightning, and because they are dry, they can burn high aboveground and spread sparks for long distances across fire lines. Felling them is dangerous work, but they can be even more hazardous if the wind determines the time and direction of their fall. The dilemma is that they also provide food and shelter for some of the fauna associated with old forests. It is wise to fell them if they are in places where they are apt to fall on people. Dead wood lying on the ground plays an important role in the life cycles of many forest organisms, both large and small.

In planning any silvicultural system, it is necessary to decide what to do about slash left in harvesting operations. The beneficial effects of slash must be weighed against the risks and problems it creates. In many humid climates, little or no slash disposal is necessary for fire control.

Many problems associated with smoke can be reduced by avoiding burning at night, or under other conditions when temperature inversions prevent upward dispersal of smoke. Allowing large pieces of fuel to smolder for days often causes smoke problems. The ideal slash disposal fire is one that burns only during the daytime and quickly consumes the fine flashy fuels that carry fires, but under conditions in which the larger fuels are too moist to burn.

Sometimes concern about smoke has led to the disposal of slash by burying it, a practice that seems hardly consistent with soil and water protection. On the other hand, if logging machines run over and crush slash that has been deposited on the ground, this will usually protect the soil from rutting, making the slash less flammable. In fact, anything that causes slash to lie close to the ground will usually speed its decomposition.

Another way to reduce forest fuels is by utilizing them; this often requires undesirably close utilization to achieve much benefit. The grazing and browsing of animals can achieve some reduction but must usually be too heavy for the health of the vegetation to break the continuity of fine fuels. The same kind of problem exists with wood utilization. Ordinarily, the wood that can be utilized comes from diameter classes larger than those of the branches and leafy materials through which forest fires actually spread. Reducing the heavy fuels may, however, cause the smaller materials to be consolidated close to the soil surface where they decompose faster than when they are supported aboveground. If partial cutting keeps shaded forest floor materials moist enough, the slash decomposes more rapidly than it would in hot, dry openings. However, the opposite effect can prevail in boreal climates as a result of low temperature.

Sometimes the continuity of slash and other forest fuels can be interrupted by establishing firebreaks along which preplanned fire lines can be built quickly to stop fires after they start. Snags and other kinds of fuels that might emit sparks that could blow over the lines, should be eliminated close to such firebreaks. Ridgetops, wetlands, and broad roads can often be developed for firebreaks which usually become stand boundaries. Fires will often stop or slow down at interfaces between

radically different kinds of forests. For example, spring fires racing through light, fluffy fuels beneath leafless deciduous forests will usually slow down when they burn into dense needle litter in the shade of evergreens. Conversely, later in the growing season after the needle litter has dried and the deciduous trees have come into leaf, a fire burning in the opposite direction will become less intense when it starts to spread in the heavy shade of the deciduous trees.

Droughts

One kind of increased stress for a forest is exposure to drought, and droughts are expected to be globally more pronounced with climate change (Allen *et al.*, 2010). Prolonged droughts are relative and can be considered abnormal periods of dryness as compared to the normal rainfall and seasonality of a climate in question. Most severe droughts are commonly associated with western North America, compared to the east, which normally has a much more seasonal climate over most of the region. Summer droughts in the west are often related to shortened periods of spring melt and reduced snowpacks the prior year, while droughts in the east are often more irregular and nearer to the end of the growing season, or almost annually in the middle-west at the woodland–prairie interface. Most species in drought-prone climates either avoid or endure such conditions through phenological, physiological, morphological, or reproductive adaptations. The relative degree of drought adaptation among species will likely determine species resilience and selection under new more extreme conditions of climate change (Hanson and Weltzin, 2000). Small increases in growing-season temperature can also increase evapotranspiration, potentially increasing drought stress among trees and species. One way of reducing potential drought stress is by reducing leaf area or stocking density through pruning or thinning respectively, but such treatments are temporary as plants seek to usurp the open and available growing space until it is closed.

Winds and Ice Storms

Winds vary dramatically in frequency, degree of strength, and scale, across North America. Hurricanes dominate the Gulf Coast of the eastern US and progressively decrease in frequency on going up the coast toward New England. Ocean temperatures in concert with regional climate and weather conditions determine the track, size, and intensity of a hurricane. It is predicted that increased temperatures with climate change will promote more intense and more frequent storms. Hurricane-adapted forests regenerate trees primarily through sprout growth and release of advance regeneration. Pine plantations in the south would be the most susceptible to damage and loss given investments made in their establishment and management and their inability to resprout or regenerate.

Convectional windstorms are also a major disturbance regime particularly on the forests of eastern North America; they are strongly associated with continental-scale frontal systems during the summer, and during the spring these downbursts often create tornadoes in the midwest and south. Combined, these kinds of storms are the most important abiotic disturbance regime of Eastern forests (Petersen, 2000). Like hurricanes, windstorms and tornadoes can create large swaths of blowdown, windthrows, and snap-offs that promote release of existing vegetation in the understory. Such storms can have enormous variability in size and strength and are predicted to become stronger and larger with climate change.

Finally, ice storms are a variant of windstorms that are significant across eastern North American forests in the late fall and early spring. They are caused by rain that moves through sub-freezing air close to the ground, and freezes upon impact on land surfaces that are below freezing. The ice that builds up on the crowns and branches of the forest canopy weighs trees down to the extent that trunks snap off and branches break. The degree of severity and extent can vary enormously from some branch breakage to total destruction. Like all the other abiotic disturbances previously mentioned, climate change is predicted to bring more frequent and more severe ice storms to the east (Irland, 1998; Covey, Barrett, and Ashton, 2015).

Climate Change

Taking droughts, fires, hurricanes, tornadoes, windstorms, and ice storms together under continued increases in global warming from emissions of greenhouse gasses, regional patterns and degree of severity of these disturbances are predicted to increase. Hundreds of studies have now documented forest mortality related to climate–water–disturbance stressors. Much of this in the western US has been characterized as forest die-off over millions of acres (hectares) of spruce in Alaska (Berg *et al.*, 2006), lodgepole pine in British Columbia (Kurz *et al.*, 2008) and the intermountain west (Jenkins *et al.*, 2008), trembling aspen in Saskatchewan and Alberta (Hogg, Brandt, and Michaellian, 2008), and pinyon pine in the southwestern US (Breshears *et al.*, 2005) (Box 26.3).

In eastern North America, there are increased and more severe disturbances, which project a forest that is more early successional. The decline and mortality of oaks appears connected to prolonged droughts in the central States (Arizona, Missouri, Kentucky) (Voelker, Muzika, and Guyette, 2008), and warmer winters appear to be linked to maple decline (Box 26.4).

Box 26.3 Predicted impacts of climate change on fire, drought, and forest decline, in western North America.

In this century it is predicted by climate scientists that the world's mean temperature will increase between 1.8 and 4.0 °C (Solomon, 2007) because of greenhouse gas emissions from the burning of fossil fuels, agricultural emissions, and deforestation and degradation. In the western US, apart from rising temperatures, climates are expected to change with increased and larger weather events – rain events (floods and mudslides), droughts (fires), and storms (winds, snow and ice). Such change is expected to impact and change the composition and dynamic of western forests. One important component that is expected to change are the relationships and interactions between droughts, winter temperatures, forest stress, bark beetle outbreaks, fires, and past cutting and fire-exclusion histories. More moderate winter temperatures are expected to increase survivals of overwintering beetle populations, with episodic outbreaks that would reach higher elevations and latitudes (Bentz *et al*., 2010). In forests that had a heavy cutting history and that were largely even-aged and overcrowded from both fire-exclusion policies of the Forest Service and a period of higher rainfall, multiple years of lower winter snowfall in recent years have promoted drought stress among much of the forest. These conditions have set the stage for both beetle outbreaks and wildfires that reinforce each other; with beetle-infested mortality of larger trees fueling wildfires, and fire-caused mortality encouraging beetle outbreaks. In more remote forest regions of the Rockies, where no such cutting history exists, wildfire and beetle activity dramatically increased in the 1980s with longer summer seasons and stronger association with increased summer and spring temperatures and earlier snowmelt (Fig. 1) (Westerling *et al*., 2006). Given the unpredictability of climate change for the future much more research is needed to understand the connections and both positive and negative interactions between the various drivers of forest disturbance.

Box 26.3 Figure 1 Mountain pine bark beetle outbreak affecting whitebark pine in Bridger-Teton National Forest in the northern Rockies. Whitebark pine is a species particularly sensitive to climate change as it is restricted to high elevations in the western US, has poor dispersal, and is sensitive to both bark beetle and blister rust. *Source:* W. MacFarlane.

Box 26.4 Predicted impacts of climate change on northeastern forests of North America.

The climate in the northeast has become warmer and wetter with an average increase of over 1.4 °F (0.8 °C) over the last century, with more dramatic warming in the winter and only moderated increases over summer. Models suggest that these shifts in temperature will exponentially increase with projected increases of 5.2–9.5 °F (2.9–5.3 °C) by the end of this century. However, contrary to the past, models suggest seasonal increases will flip with summers having much higher increases in temperatures than winters. Precipitation increased by about 4 in (10 cm) in the 20th century, with most of this increase occurring in the spring and fall. Both the intensity and frequency of precipitation events have increased, but periods between events, particularly in late summer and fall, receive little rain, making for more frequent and intense droughts. Rainfall is expected to increase another 2.8–5.7 in (7–14 cm) by the end of this century, from its current mean of about 41 in (104 cm). Wintertime snow packs are declining, ice-free lake days are increasing, peak stream flows are earlier in the spring (March), and low flows will be earlier in the summer. Rain on snow events will

Box 26.4 (Continued)

increase, wintertime infiltration will decrease because of increased rain on frozen soil (Table 1). It is expected that decomposition of soil organic horizons will increase and leachates will remove more base cations (Table 1).

These climate changes suggest forest composition and successional dynamics will change. Boreal and alpine forests of spruce–fir will shift upward in elevation and northward in latitudes. Evidence for these shifts already exists. Southern oak–hardwoods are expected to incrementally shift north into the northern hardwood of maple–birch–beech forests which in turn will replace the spruce–fir. All of these forests will be impacted by increased disturbances (e.g., ice-storms, flooding, convectional windstorms, and prolonged droughts). To promote forest adaptation, silvicultural focus should be on developing greater structural, compositional, and age–class complexity through the use of irregular shelterwood, seed-tree, and variable selection (single-tree, group and patch) methods. Increasing the establishment and vigor of advance regeneration can be done as a reserve vegetation bank capable of immediate site stabilization and release after disturbance to the forest canopy. Increasing the functional diversity of species groups and age-class structure of forests reduces risk (D'Amato *et al*., 2011).

Much of the information for Box 26.4 has been distilled from Rustad *et al*., 2012.

Box 26.4 Table 1 Predicted changes in ecosystem processes in a northern hardwood forest with changing climate.

Biogeochemical changes	Hydrological changes
Ecosystem level processes	**Summers**
Increased levels of decomposition	Hotter
Increased loss of soil carbon	More intensive periods of drought
Loss of bases through leaching and erosion	Lower late summer stream flows
Loss of nitrogen	Warmer waters
Lower net primary productivity	Increased transpiration stress
	Winters
	Milder
	Reduced snowpack
	More intense storms
	Frozen soils – less insulated and more exposed
	More runoff and less infiltration

Source: Mark S. Ashton.

Using Silviculture to Control Damage

Certain kinds of cuttings are sometimes done in attempts either to anticipate damage or to prevent it. **Pre-salvage cutting** is designed to anticipate damage by removing highly vulnerable trees. **Sanitation cuttings** are more active measures designed to eliminate trees that have been attacked, or appear in imminent danger of attack, by dangerous insects and fungi in order to prevent them from spreading to other trees. **Salvage cuttings** are done to save the wood in dead or damaged trees. The opportunity to engage in such races with the damaging agencies depends mainly on whether stands are sufficiently accessible.

Pre-Salvage Cuttings

The rational conduct of pre-salvage cuttings depends on identifying those trees that are likely to be lost and estimating the length of time they may be expected to endure. If the main source of anticipated damage is wind, ice, or some other climatic agency, the mechanical structure of the trees and their position within the stand are the important criteria. Trees with asymmetrical crowns or previous injury from frozen precipitation are prone to additional damage from this source.

When biotic agencies or physiological factors, such as those related to site factors, are the causes of anticipated losses, the vigor of the trees is usually the criterion employed in pre-salvage cutting. Trees of relatively high vigor are less vulnerable if attacked because they are likely to endure the amount of loss of vital tissues that would kill trees of low vigor. Abundant pitch flow from trees of good vigor even actively resists attack by *Dendroctonus* bark beetles, which dictate much pre-salvage cutting. The pre-salvage of trees of low vigor is rendered all the more logical because they grow little in volume or value. A number of tree classifications has been developed as a guide to pre-salvage cutting (Hedden, Barras, and Coster, 1981). One of the best-known examples of such a classification is that developed by Keen for the interior ponderosa pine type of California and the northwest US (Miller and Keen, 1960). Vulnerability to loss from bark beetles is so closely related with growth rate that this classification is suitable for selecting trees for cutting, even where risk of beetle attack is not the main consideration.

Keen's classification (Fig. 26.5) is based on the two major factors of age and crown vigor. There are four

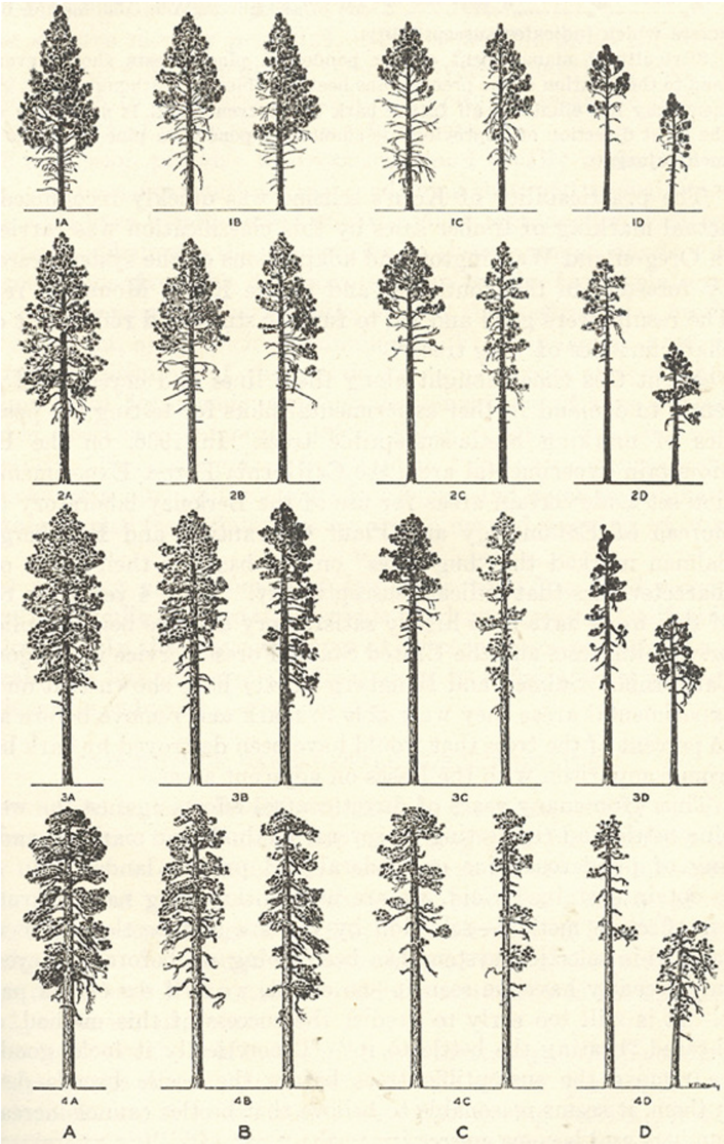

Figure 26.5 The Keen tree classification for ponderosa pine. The four age classes range from 1, the youngest, to 4, the oldest; the four crown vigor classes range from A, the most vigorous, to D, the poorest. *Source:* US Forest Service.

age classes and four vigor classes within each age class, making a total of 16 classes. The four age classes are termed: (1) young, (2) immature, (3) mature, and (4) overmature. They are grouped by relative maturity rather than by any definite age range. Actual age limits for the groups vary in different parts of the ponderosa pine region. Color and type of bark, total height, shape of top, characteristics of branches, and diameter, are the chief external indications of maturity. The four crown vigor classes are: (A) full vigor, (B) good-to-fair vigor, (C) fair-to-poor vigor, and (D) very poor vigor. The size of the crown (length, width, and circumference), its density, and the shape of its top, indicate the crown vigor, and consequently the inherent capacity of the tree to grow and endure exposure to beetles.

Keen's classification was originally designed to provide a means of evaluating the risk that the trees left after selection cutting would be attacked by beetles during a cutting cycle of approximately 30 years. Although it still serves as a useful guide for many kinds of partial cutting and as an example of a tree classification, simpler means are now being used to determine which trees are in imminent danger of death. This is because it is possible to make much lighter pre-salvage cuttings at much more frequent intervals.

Sanitation Cuttings

Sanitation cuttings are often combined with salvage or pre-salvage cuttings. In fact, any cutting may be considered sanitation cutting to whatever extent it eliminates trees that are present or prospective sources of infection for insects or fungi that might attack other trees. Sanitation cuttings are not worth conducting unless the removal of susceptible trees will actually interrupt the

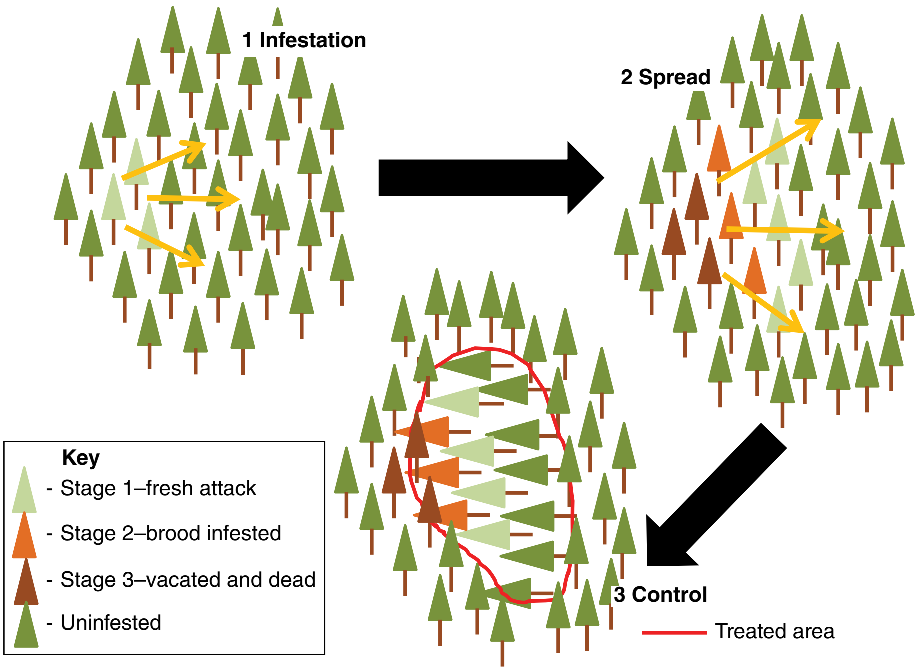

Figure 26.6 Controlling the southern pine beetle (*Dendroctonus frontalis*) through controlled cutting treatments. (1) Initial spot infestation by beetles with direction of spread. (2) Spread of beetle infestation to trees responding to aggregation pheromones. (3) Control through cut-and-leave treatment that disperses emerging beetles that no longer can concentrate in areas with aggregated pheromones. Dispersed beetles have a low probability of surviving to start another infestation. *Source:* Mark S. Ashton.

life cycle of the organisms sufficiently to reduce their spread to other trees. For example, the elimination of *Ribes* shrubs from stands of five-needled pines can be a moderately effective kind of sanitation treatment (or weeding). However, the removal of pines already infected with the blister-rust fungus is not effective sanitation, because the spores that carry *Cronartium ribicola* from pine to *Ribes* can travel so far that no practical advantage is gained. Sanitation cuttings are often applied to reduce the spread of *Dendroctonus* bark beetles in the southern pines, ponderosa pine, and Douglas-fir (Fig. 26.6).

It should not be tacitly assumed that the vigor of trees is the sole criterion of susceptibility to attack, even though it may be a good indicator of their capacity to endure damage. Some economic pests of the forest, notably insects, multiply most rapidly on vigorous hosts, just as grazing animals prefer forage from healthy plants. Fortunately, the vast majority of insects attracted to vigorous trees do not endanger their own existence by killing their hosts; these insects rarely become cause for concern.

Sometimes sanitation cuttings must be associated with special measures to provide additional assurance that the damaging organisms will not spread to the residual stand. If the insect or pathogen exclusively depends upon living tissues, it is sufficient to kill the infested trees and leave them in the woods. If the insects or fungi involved are capable of multiplying as saprophytes in dead material, it may be best to utilize the wood even at a loss, provided that its transportation does not spread the infestation. This approach can be used to increased advantage against bark beetles if "trap" logs or trees are left temporarily to attract them, and then hauled to a mill or log pond before the emergence of the entrapped brood. It may also help to burn slash or treat stumps with insecticides in ways that directly kill the beetles.

Those species of heart-rotting fungi that spread as spores from conks on fallen trees are not easy to control if infected logs must be left in the woods. However, the felling of infected trees does reduce the distance over which the spores can travel, and the accelerated disintegration of the wood shortens the period of danger.

There are some types of damage against which sanitation cuttings are ineffective for practical purposes. Fungi that inhabit the soil and damage the roots of trees (such as *Heterobasidion annosum*) are not likely to be halted even by sanitation cuttings that are carried to the extent of removing the stumps. Some organisms spread so rapidly or over such long distances that sanitation cutting may be a meaningless gesture as far as the effective protection of the stand is concerned.

Sometimes the cutting of entire stands may be regarded as a desirable measure of sanitation, even if the damaged stands by themselves are not worth the effort. Stands that have been badly damaged by fire, wind, or similar agencies, frequently support the development of large

populations of bark beetles that can cause serious injury to adjacent stands. The expense of an operation that cuts the whole stand may be sufficiently rewarded by reducing losses in adjacent stands.

Salvage Cuttings

When all else has failed, it may be desirable to salvage the dead and dying trees. Salvage cuttings are made for the primary purpose of removing those trees that are imminently threatened by mortality, damage, or loss from injurious agencies other than competition between trees, or that are already dead but are still merchantable. Salvage treatments should not be regarded as a method to control the insect or pathogen (e.g., sanitation cuttings), but merely allows a landowner to redeem some of the value that has been lost. Obviously, salvage would not be a treatment to consider for landowners with multiple values and where merchantable timber is secondary. In fact, standing dead and down timber has unique wildlife habitat characteristics that may be very important to the landowner, and in these circumstances should be left alone. A second example of where salvage should be avoided is where slopes and soils are susceptible to erosion and compaction.

In some cases, attacks by damaging agencies are so chronic that they rule silviculture. One example of this distressing state of affairs exists on the badly eroded, poorly aerated soils of the Piedmont Plateau, where shortleaf pine is often lost to the little-leaf disease and root rots. Unfortunately, it is replaceable only with other pines that are vulnerable to fusiform rust and bark beetles. Salvage cuttings essentially repeat themselves by responding to one disease and then another in a never-ending cycle.

The recovery of timber values that might otherwise be lost is one important and expeditious silvicultural means of securing yields greater than those available from the managed forest. The objective is usually to utilize the injured trees to minimize financial loss. Salvage cuttings are not conducted unless the material taken out will at least pay for the expense of the operation, except in cases where real justification exists for true sanitation cuttings. Salvage operations are often not feasible unless they are combined with the removal of healthy trees in other silvicultural operations such as thinnings or regeneration cuttings.

The immediate financial loss depends largely on the extent and distribution of damage. If trees die sporadically and at widely scattered places in a stand, they may become a total loss because of the impracticability of harvesting them. The loss may be small if the amount of damage is not great and is concentrated in time and space. When catastrophic losses have occurred over a wide area, the returns from salvage cutting are often reduced by the necessity of selling the products on a glutted market. The costs of logging are generally higher in salvage cutting than in operations where the trees to be removed have been chosen by intention rather than by accident.

Identifying the trees to be taken out in salvage cuttings is not usually a problem. However, sometimes the mortality caused by the attack of a damaging agency does not take place immediately. This is particularly true where surface fires have occurred, because the main cause of mortality is the girdling that results from killing cambial tissues. As with other kinds of girdling, the top of the tree may remain alive until the stored materials in the roots are exhausted. It is usually a year or more before the majority of the mortality has occurred. By this time, those trees that were killed immediately have often deteriorated seriously. Thus, it is advantageous to anticipate mortality before it has actually occurred. The predictions must be based on outward evidence of injury to the crown, roots, or stem.

Salvage cuttings should be completed as soon as possible after mortality or injury has occurred. Dead trees generally start to deteriorate rapidly during the first growing season after death, so it is usually advisable to get the trees out of the woods before insects and fungi have become active in the spring.

Unfortunately, the amount of salvageable material is often so great that it cannot be removed within a few months or a year, even if all other operations are suspended. Under such conditions, it is highly desirable to know how long the dead or damaged trees are likely to remain sufficiently sound to be worth salvaging. Entomological and pathological investigations have made this information available for a number of different species (Boyce, 1961). This type of knowledge makes it possible to conduct large salvage operations systematically and efficiently.

The amount of time allowable varies widely depending on the circumstances. The sapwood of virtually all species is highly perishable, but the heartwood of the most durable may remain sound for many years. Dead trees of small diameter become valueless long before large trees. Deterioration usually proceeds more rapidly on good sites than on poor. Differences in the rate of decay of various species are also significant. The basic objective should be to schedule salvage operations in different places in such order that the value of timber saved will be at a maximum. This does not necessarily mean that the most valuable material should be salvaged first, because some less valuable wood may deteriorate much faster.

Harvesting of damaged timber is often more difficult and expensive than cutting in undamaged stands. This is especially true if large groups of trees have been broken off or uprooted by wind. In conducting salvage operations, the money lost because of expensive logging can easily exceed the potential values wasted from the decay of unsalvaged timber. The extremes of both haste and procrastination should, therefore, be studiously avoided in salvage cutting.

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27

Managing Forest Carbon in Changing Climates

Introduction

Managing, protecting, and restoring forests is one part of an integrated solution toward mitigating the impacts of climate change. Forests cover about 16 million square miles (40 million km^2) of the global land surface, representing about 45% of terrestrial carbon and providing about 50% of the world's terrestrial **net primary production** (NPP) (Bonan, 2008). Forest carbon uptake amounts to 2.6 Pg carbon per year or about 33% of carbon emissions from fossil fuel and land-use changes (e.g., deforestation and conversion to agriculture, forest degradation from logging) (Bonan, 2008). The use of forests and silviculture to mitigate climate change has gained the interest of policy makers and natural resource managers who have been studying the effects of **greenhouse gas** (GHG) emissions since the beginning of the 21st century. This chapter examines the carbon science of forest soils, stand dynamics, and global forest trends, the pros and cons for managing carbon, and the environmental costs and benefits. This will be presented in four sections: (1) understanding the ecology of forest carbon; (2) strategies to sequester carbon by increasing forest area through reforestation/afforestation and/or strategies for avoiding carbon loss from deforestation; (3) strategies for increasing carbon storage through management in existing forests; and (4) strategies of using wood as biomass energy in place of other building materials, or in wood products to increase carbon storage and use wood instead of other high-energy materials.

The Ecology of Forest Carbon

Soil Carbon

In current policy, much discussion deals with the role that forests are expected to play in storing additional carbon as part of the global initiative to offset the buildup of anthropogenic carbon dioxide (CO_2) in the atmosphere (IPCC, 2007). A significant proportion of total terrestrial carbon is stored and cycled as **soil organic carbon** (SOC). However, the amounts stored and the changes over time are poorly understood due to difficulty in monitoring and measuring the complexity of belowground interactions that involve the carbon at depth. Land-use changes and disturbances can create legacy signatures that can affect carbon storage in soils for decades and even centuries. Such effects can confound results of any short-term field studies that have recently started to investigate and document soil carbon changes. For example, the forest land clearance and colonization of the eastern forests of North America for agriculture had a profound influence on soil-forming processes that is still apparent after 150 years of agricultural abandonment and second-growth forest development.

Much work has been done that has provided an understanding of many soil carbon processes. For instance, much is known about how **dissolved organic matter** (DOM) from processes of litter decomposition infiltrate the mineral soil (Michalzik *et al*., 2001; Park and Matzner, 2003). This process is one important long-term carbon-storage mechanism. It is also recognized that fine roots are the main source of carbon additions to soils from root turnover or from root exudates associated with symbiotic mycorrhizal fungi. It is known that the relationship between nitrogen deposition and carbon storage differs on soils with low-quality, high-lignin litter, as compared to soils with high-quality, low-lignin litter (Knorr, Frey, and Curtis, 2005). Such findings have provided one explanation for many studies that have seemingly been contradictory in regards to the effects of nitrogen deposition. Studies have also shown that about half of the respired CO_2 from the soil comes from roots and mycorrhizal fungi, while the other half is from heterotrophic bacteria that break down organic matter in the decomposition process (Ryan and Law, 2005). All of these interacting components of fungal, root, and bacterial processes clearly have a significant effect on carbon storage and release. Microbes can stabilize organic matter by biochemical resistance or by physical protection within soil aggregates. Poor drainage (hydric conditions) and fire (deep charcoal) can also stabilize organic carbon by

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starving microbes and processes of decomposition from lack of oxygen (Czimczik *et al.*, 2003; Jarvis *et al.*, 2007).

Anthropogenic influences from fossil fuel burning and wind erosion of agricultural soils as well as particulates from forest fires are hypothesized to affect microbial breakdown of organic matter and alter forest nutrient cycling (Loya *et al.*, 2003; Sinsabaugh *et al.*, 2005). However, only a few studies have investigated these phenomena and no clear understanding has yet developed. Other work that is needed is to: (1) characterize how **dissolved organic carbon** (DOC) and leaching are regulated by the thickness of the organic layer; (2) understand how rates of fine root turnover differ among species and biomes; (3) understand how bacterial, fungal, and plant respiration and their interactions are affected by physical stresses (such as drought, increased temperature); and (4) understand the dynamics of functionally distinct soil carbon pools, rather than those carbon pools that have been more traditionally easy to measure.

Thus far, studies on soil carbon have been restricted to agricultural soils of the developed regions of the temperate world, and to within the top 12 in (30 cm) of the soil profile. Forest soils in tropical moist regions are represented by only a few studies, as are examinations of sequestration of carbon at depth (Price, Bradford, and Ashton, 2012). However, the biggest dominant storehouse of soil carbon is at higher latitudes and its fate under climate change is very uncertain. Studies need to examine responses of this carbon store to changing climate. What is now needed is a globally distributed and coordinated research program to measure soil carbon.

Stand Dynamics

The most effective way to date of understanding stand response to climate changes has been from the **Free Air Carbon Exchange** (FACE) experiments that have been set up throughout the temperate realms (mostly in North America and western Europe). These experiments pumped extra amounts of CO_2 and manipulated temperature over young stands of trees, and then monitored their growth response (McLeod and Long, 1999; Norby *et al.*, 2005; Asshoff, Zotz, and Korner, 2006; Oren, 2008). Many have been running (or ran) for over two decades with results showing net primary productivity, and thus, carbon uptake usually increases when atmospheric carbon dioxide levels increase. This is due to a variety of factors including increased nitrogen-use efficiency (Norby *et al.*, 2005; Luo, Hui, and Zhang, 2006; Springer and Thomas, 2007) and increased competitive abilities of shade-tolerant species (Kerstiens, 2001; Mohan, Clark, and Schlesinger, 2007). In addition, experiments that create droughts are demonstrating that water availability may be the most important factor influencing fluxes in carbon and its sequestration in forests (Finzi *et al.*, 2006). All of these experiments have not been operating long enough to predict eventual or long-term response of forests to changes in rainfall, temperature, or increased CO_2. This leaves scientists to make predictions using multifactor models that are often based on large assumptions that in cases have proven wrong.

If predictions are to be made regarding stand-level carbon within forest ecosystems, it is important to have an understanding of what scientific research has or has not established. Key findings support the notion that the stem-exclusion stage in stand development is a period of high carbon assimilation, water uptake, and nutrient acquisition, but many recent studies are showing that old-growth forests are doing the same. In other words, old-growth is not just storing carbon but is also sequestering significant amounts. FACE has provided a near-term understanding of the positive and negative responses and feedbacks that elevated CO_2 can have on the physiological and stand-level ecology of forests. With no disturbance, forests are expected to increase CO_2 sequestration and increase water-use and nutrient-use efficiencies, and favor shade-tolerant species. Experiments on rainfall exclusion and addition, and investigating drought and excess water, have provided insight into the reallocation of carbon belowground, with increased avoidance and endurance adaptations with drier conditions. Important findings that influence forest change include the timing of when the drought occurs (growing versus non-growing season) and changes in species composition.

Although many studies have provided us a better understanding of successional and stand dynamics, there is enough variability in limiting factors (e.g., soil fertility), species composition change, stocking, and rates of growth to make forest responses to climate change and elevated carbon more unpredictable than originally thought.

FACE studies have been limited to temperate and boreal biomes mostly in the stem-exclusion stage. In addition, similarly to soils, carbon stocks and fluxes of stands of different developmental stages across and within different forest biomes, particularly in the tropics, have not been well documented. More studies are needed that investigate the multiple interactions of limiting and non-limiting resources of soil nutrients, soil water availability, and temperature fluctuations in elevated carbon dioxide environments.

Global Forest Patterns

Although large amounts of carbon are stored and continue to be sequestered in forests, providing a net benefit by reducing carbon dioxide emissions, their low surface albedo (meaning that forests absorb heat and light energy well relative to other land surfaces) can

contribute to planetary warming as compared to the higher albedos of cleared lands that are bare or retain snow (meaning that much of the incoming energy is reflected back out to space rather than absorbed). However, because forests provide much greater amounts of evapotranspiration as compared to other land uses, they also serve to cool climates indirectly through clouds and precipitation. For instance, climate models for the Amazon basin have depicted the presence of forests to decrease surface and air temperatures and to increase precipitation because of their high evapotranspiration rates as compared to lands cleared for agricultural use (Nepstad *et al*., 2008). The warming because of the low albedo of forests in the Amazon is more than offset by their evaporative cooling properties. Such properties provide similar effects across the tropical forests of central Africa and Southeast Asia, and that their cooling effects transcend to neighboring regions of the subtropics through atmospheric feedbacks and connections (Bonan, 2008). This is partly because, even during the dry season, tropical forests sustain evapotranspiration (da Rocha *et al*., 2004; Huete *et al*., 2006) and are significant sinks in carbon, both mitigating climate warming. However, tropical forest clearance could greatly exacerbate climate warming through positive feedbacks that cause dramatic declines in the cooling powers of evapotranspiration and releases of both stored soil and vegetation carbon.

For temperate forest regions, much of the area has been formerly cleared for agriculture and now reverted back to second-growth forest (e.g., eastern North America, Europe, and China). Agricultural lands have a higher albedo and therefore cooling effect than forests, but the forests, because most are still growing, have much higher carbon sequestration and evapotranspiration that increases clouds, water vapor, and cooling during the summer (especially for deciduous forests), masking the warming from higher albedo (Baidya Roy *et al*., 2003; Jackson *et al*., 2005). However, in the intermountain and midwest, irrigated crops during the growing season can increase cooling from evapotranspiration compared to native coniferous forests. Higher albedo from deforestation may negate the cooling effects of evapotranspiration from forests.

Boreal regions that are deforested or have been recently regenerated have higher albedo because of the higher presence of snow that serves to cool climate as compared to a mature coniferous forest. Compared to the other forest biomes, this effect is the most significant (Synder, Delire, and Foley, 2004). Although boreal forests have lower rates of carbon sequestration, they have much greater stored pools of carbon belowground through permafrost soils, wetlands, and peats, than any other forest biomes. Wildfires that can dramatically impact boreal forests cause substantial greenhouse gas emissions from organic soil combustion, but the effect on climate is less than the overall post-fire albedo cooling from young regenerating forests (Randerson *et al*., 2006). This may be amplified by shifts from evergreen to deciduous forest types, or more muted in the reverse case.

Additionality and Permanence

When carbon emissions are avoided when conducting forest management, it is termed **additionality**. This refers to management that purposely intends to change behavior from the normal business-as-usual activities. Three approaches are possible: (1) creating carbon additionality by creating new forests on open lands; (2) protecting intact forests thus protecting stored carbon that would otherwise be released from land clearance or logging (so-called **avoided deforestation**); and (3) minimizing the carbon lost in existing forests that are managed primarily for other products and services (e.g., timber). **Permanence** is another term that is used to define whether additionality of carbon has the long-term stability to remain sequestered through reforestation, protected through avoided deforestation, or increased through improved management practice. All too often, negative feedbacks can reduce additionality through fires, insects, diseases, and land tenure changes that had not been planned or accounted for. Such feedback would be defined as not having permanence.

Forest-management practices and methods must therefore increase carbon stored within forests when compared to some baseline measure to qualify for additionality (Lugo, Silver, and Colon, 2003). Examples include reforestation on degraded lands, or when management practices (e.g., reduced-impact logging) are implemented that minimize the amount of carbon lost in comparison to business-as-usual logging practices using a set of baseline management conditions.

Avoiding Deforestation and Increasing Reforestation

Afforestation and Reforestation

Reforestation with plantations and natural regrowth of secondary forests both can be good examples of carbon sequestration when applied in the appropriate contexts (Hodgman *et al*., 2012). Both can present an opportunity for climate change mitigation and adaptation. In climate change policy discussions, planted and natural secondary forests are placed in the category of afforestation and reforestation (A/R) projects. Temperate regions currently contain most of the existing planted and naturally regenerating forests. However, establishment of new forests is fastest in the tropics, especially Southeast Asia and Latin America (Fig. 27.1).

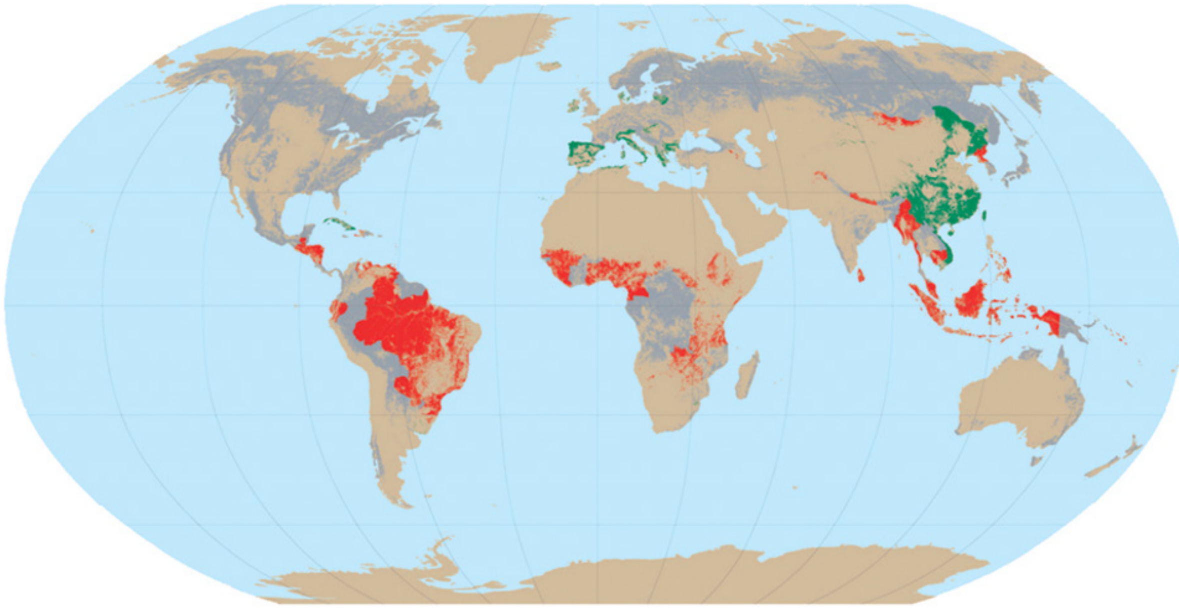


Figure 27.1 Global map of net deforestation (red), net reforestation (green), and neutral, where deforestation and reforestation regionally balance each other out (gray) from 2000–2005. *Source:* Food and Agriculture Organization of the United Nations.

Reforestation policy based on climate-mitigation science would suggest that the best benefits are programs implemented in the tropics, because of increased evapotranspiration, clouds, and cooling with carbon sequestration from regenerating forests. Alternatively, models suggest that reforestation in the boreal regions would have limited climate benefits because of reduction in albedo effects (Betts, 2000; Bala *et al.*, 2007; Hodgman *et al.*, 2012). Temperate regions would also have limited benefits if large albedo changes that favored lower reflectance occurred.

There are several important factors that need to be considered for all A/R projects when considering carbon sequestration. The first factor is **site selection** (Hodgman *et al.*, 2012). Some sites are much more productive than other sites. These obviously tend to be more in demand for other economic values as well. However, certain sites can be efficient at sequestering carbon within soils through the actions and influences of vegetation (e.g., spodosols). Reforestation can also be an important mechanism to increase soil carbon on old agricultural lands in many circumstances. On inappropriate sites, planting projects can result in losses of soil carbon. This is especially the case on afforestation of natural grasslands. In addition, newly established forests (native or planted) can negatively affect groundwater and surface water flow and amounts, and reduce biodiversity. While opportunity exists for carbon sequestration projects, carbon should thus not supplant all other forest values. Rather, managers should treat carbon as one of many management objectives for forests.

The second consideration is **species selection**. Selecting the right species for any given site is critical for any reforestation project (van Breugel *et al.*, 2010), but it is very important if the desired outcome is to maximize carbon sequestration. Some mixed-species plantings have the potential to store more carbon than single-species plantings but to secure such gains, species mixtures have to be complementary or, even better, facilitatory (see Chapter 14). The advantages of some single-species plantations are that they are easy to manage and have benefited from many years of genetic selection for tree growth because they are usually important timber trees.

Some common management practices that effect forest carbon sequestration and that are associated with planting include: (1) site preparation, which, if it exposes the mineral soil, can cause a loss of soil carbon and, because of the mechanical equipment used, can involve significant fossil fuel emissions; (2) fertilization, which can dramatically increase tree growth and carbon sequestration but its production is a source of greenhouse gas; (3) herbicides, which can reduce vegetative competition and can increase tree growth and promote earlier canopy closure; (4) irrigation, which can dramatically increase tree growth but may be expensive, ecologically inappropriate, or impractical.

Finally, there are important policy issues that need to be considered for reforestation and afforestation. Afforestation includes many sites and regions that have never had trees historically. Under such circumstances, resource managers and policy makers need to be aware that planting trees on such sites often has adverse effects on other values, particularly related to water and biodiversity (Farley, Jobbagy, and Jackson, 2005; Bala *et al.*, 2007). Policy makers also need to protect or incentivize other ecosystem services besides carbon to help ensure that negative side effects of A/R projects do not occur. Large, industrial, single-species plantations developed by institutional investors can easily dominate A/R projects. Ways need to be found to make native and mixed-species plantations economically competitive with single-species systems because, in some cases, they offer additional carbon storage and reduced risk of carbon loss from pests and disease (Siddique *et al.*, 2008).

Avoided Deforestation

If reforestation is one strategy to sequester carbon, then avoided deforestation and degradation can be considered the other strategy. Avoided deforestation and degradation can be considered a strategy that reduces carbon loss by forest conversion to other uses, or by eliminating poor and degrading management practices. Estimates suggest that carbon losses from forest conversion or poor management contribute about 15% of total annual global greenhouse gas emissions. In recent years, negotiations by policy makers have worked to develop solutions to climate change that incorporate forests. Silvicultural practices can be an integral part of reducing carbon loss and improving carbon storage. One aspect to focus on improving and strengthening is sustainable forest management. Carbon uptake and storage in forests can vary widely based on geology, hydrology, soils, and climate. For primary forests that have high carbon storage, emphasis must be placed on their protection. This is particularly the case in the wet tropics. In the tropics, **reduced-impact logging** (RIL) is a mechanism to reduce carbon emissions (Dykstra and Heinrich, 1996). In some temperate countries this is law and would be considered **best management practice** (BMP). RIL practices include planned skid trails, directional felling, and minimizing injury to other standing trees. This is considered standard practice in other forest regions. It is therefore important to move beyond RIL in the tropics to substantially increase carbon storage by developing more sophisticated planned forest-management schemes with silvicultural treatments that ensure regeneration establishment, post-establishment release, and extended rotations of new stands. Forests can be financially viable compared to other land uses through integration and cultivation of species that provide timber and non-timber products that are stacked (cumulative) and that are compatible with service values, such as carbon sequestration and water quality (see Chapter 28).

To fulfill the many resource needs that forests provide but at the same time increase carbon storage, it is critical to engage in better stand-level and landscape-level planning. For example, many logged-over and second-growth forests are ideal candidates for rehabilitation with enrichment planting of supplemental long-lived canopy trees for carbon sequestration (FAO, 2006; Asner *et al.*, 2010). These same forests are still storehouses of biodiversity and provide important watershed protection. The largest potential source of carbon sequestration in the tropics is the development of second-growth forests on old agricultural lands. Every incentive should be provided to encourage the process of reconversion of agricultural lands back to forest, particularly on lands that are considered marginal and were once forested (Mather and Needle, 1998; Rudel *et al.*, 2005).

Carbon Management in Existing Forests

If carbon storage and sequestration/loss amounts are considered an important component of mitigating climate in existing forests that are managed, then silvicultural treatments that are most effective at maintaining or increasing carbon need to be incentivized. This strategy can be considered one in which silviculture of existing forests, that are not threatened with conversion or degradation, can be used to better manage forests for additional carbon gains. The best example of this practice and strategy to date in the US is the State of California's carbon credit program (Heffernan *et al.*, 2009). However, there are other national examples elsewhere (Box 27.1).

Forest management can affect carbon in the positive and in the negative, but it can also be complex. There are many examples of this. For instance, the drainage of wetlands for increased growth and timber production can result in either net carbon gain or loss, depending on how deep the drainage (Cannell, Dewar, and Pyatt, 1993). Silvicultural thinning causes a reduction of the aboveground stored carbon which can recover over a matter of decades. However, in addition, the amount of carbon stored in forest products, emissions from management operations, and fossil fuel displacement by forest biomass, determine whether or not practices like thinning are positive, neutral, or negative. In fire-prone forests of western North America, fuel-reduction treatments such as thinning, chipping, and use of prescribed fire, can result in lower standing carbon storage. However, more resilient forests are much less susceptible to catastrophic stand-replacing wildfires that would destroy all or almost all aboveground stored carbon (Dore *et al.*, 2010).

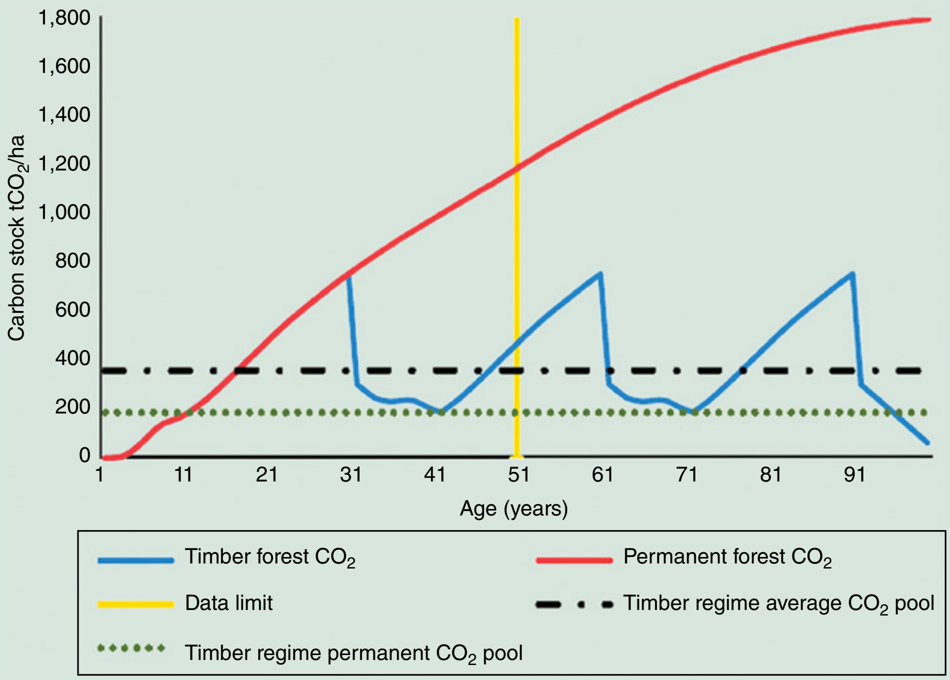
Box 27.1 A national carbon-mitigation strategy for private landowners: an example from New Zealand.

Several studies suggest that forest-management strategies could offset US fossil fuel emissions by 10–20%. This would require a combination of afforesting up to one-third of cropland or pasture land, using the equivalent of about one-half of the gross annual forest growth for biomass energy, or implementing more intensive management to increase forest growth on one-third of forestland. Such offsets would have tradeoffs, such as lower agricultural production and non-carbon ecosystem services from forests. The effectiveness of such activities could also be diluted by negative leakage effects and increasing disturbance regimes.

Forest policies to encourage programs to increase carbon sequestration and offset fossil fuel emissions thus need to consider leakage, the forest growth and regrowth cycle, the use of forest products as a substitute for more energy wasteful products, other greenhouse gas effects (e.g., methane, nitrous oxide emissions), and recognition of other environmental benefits that forests provide (e.g., biodiversity, nutrient management, and watershed protection).

The Permanent Forest Sink Initiative (PFSI) is one such program that was adopted by New Zealand in 2006. The New Zealand government is the guarantor of the scheme which involves issuance of carbon credits to legally certified landowners who reforested their lands after 1990 and who participate in PFSI. The landowner is obligated to ensure the land will be maintained as forest for 99 years and credits will be issued to the landowner for increasing carbon stocks. Clear-felling is prohibited but timber harvesting is permissible for thinnings, provided there is some form of continuous canopy and the harvest timber is not greater than 20% of the basal area (Fig. 1). Any carbon lost through timber harvest or natural disturbance (e.g., fire) has to be repaid to the government.

An application and successful registration of land can be fast (within 4 months), and monitoring is made every 5 years to ensure carbon storage exceeds baseline amounts. Insurance can be issued to cover against loss of carbon. Since the scheme began, about 20,000 ha have been registered. For comparison, there are 1.75 million ha of plantation land (7% of the land area of New Zealand) and 6.5 million ha of native forest, most managed by the government.



Box 27.1 Figure 1 Carbon stocks (t CO_2/ha) of planted radiata pine forest in NZ from time of planting to 100 years of age. The timber regime is clear-felled every 30 years releasing stored carbon. Data on which the modeling is based is statistically 'rich' from 0–50 years and 'poor' from 50–100 years. *Source:* Belton, M. 2012. Magazine, www.silviculturemagazine.com

Even-aged regeneration treatments can significantly reduce carbon stocks aboveground and cause an increase in soil respiration for a period. However, the young regenerating stand will have a high rate of sequestration, much greater than any other period of stand development, but it will still take at least 10–30 years before aboveground carbon uptake is greater than carbon loss and the stand becomes a sink rather than a carbon source

(Howard *et al.*, 2004; Fredeen, Waughtal, and Pypker, 2007). Many of these examples are of silvicultural treatments that are appropriate for a variety of important social and biological values (e.g., wildlife habitat, timber, and non-timber forest products) but not for ensuring maximum carbon storage and sequestration. Such treatments thus result in net carbon release and cannot demonstrate carbon additionality. Mechanisms therefore need to be developed to credit projects that reduce carbon loss by the lowest amount possible, in addition to those that increase carbon gain. Baselines need to be set for forest carbon project accounting that will allow determination of which management activities should be incentivized.

There are some obvious silvicultural treatments that can be employed to prioritize increases in carbon stocks and sequestration and thus create additionality. The most prominent example is where carbon sequestration is increased by extending rotation lengths (Foley, Richter, and Galik, 2009; Carrol *et al.*, 2012), especially if maximum biomass productivity has not yet been reached. In general, the lighter the thinning and the greater the amount of structure and mature trees left behind in a regeneration method, the more compatible the silviculture toward storing carbon (Taylor, Wang, and Kurz, 2008; Nunery and Keeton, 2010; D'Amato *et al.*, 2011). In addition, the greater the shift in species composition to later-successional species with denser woods and higher carbon densities, the greater the proportional amounts of carbon stored per unit volume of wood biomass. Facilitating successional time and age of stands through passive processes and small low-intensity treatments to facilitate shifts to long-lived species with denser woods is perhaps all that is necessary to maximize standing carbon storage (Keeton, 2006; Rhemtulla, Mladenoff, and Clayton, 2009; Bradford and Kastendick, 2010; D'Amato *et al.*, 2011). There is a point of diminishing returns when rotations are extended beyond the age of maximum biomass productivity and growth declines because of various physiological limitations.

At some point, it may be possible to store more carbon in a series of short rotations that maintains the stand in a young, productive stage, rather than a single longer rotation, particularly if the wood harvested is efficiently converted to a wood product with a long lifecycle. Fertilization can increase carbon storage in vegetation and reduce soil respiration rates, but this needs to be balanced by the emissions costs of producing the fertilizer (Markewitz, 2006). In such circumstances, the alternative is potentially to use nitrogen-fixing trees or ground covers as a complement, if appropriate. Resiliency treatments to make forests more fireproof result in lowered carbon storage and some carbon release from decomposition and combustion, but create less susceptible forest to stand-replacing fires and huge carbon release (Finkral and Evans, 2006; Dore *et al.*, 2010; Carrol *et al.*, 2012). If old forests already exist, maintaining them as old forests maximizes carbon storage. Old forests, especially on productive sites, often have very large pools of vegetative carbon in comparison to forests managed on shorter rotations. Soil and litter pools may also be large in old-growth forests, and in the boreal, the bryophyte pool as well. The conversion of old growth to managed forests likely results in a loss of ecosystem carbon that cannot easily be regained (Keeton, 2006).

Finally, carbon **leakage** must be recognized. Carbon sequestration strategies cannot simply implement improved efficiencies and silvicultural treatments in one place only to displace that improvement by heavier timber harvests, shorter rotations, or more intensive site treatments elsewhere.

The Use of Wood as Biomass Energyor in Wood Products for Carbon Storage

Although carbon sequestration and climate mitigation are recognized by policy makers as important roles that forests play, there is currently no accepted protocol for quantifying and incorporating harvested wood products for carbon credits. Discussions rarely consider how wood products and the lifecycle of wood can be linked to the forest as a potential compounding positive effect on global climate mitigation.

Understanding what role **harvested wood products** (HWPs) can play in the global carbon cycle is an appropriate component of managing forests for carbon storage and sequestration. The treatment of HWPs as a carbon stock could be incorporated into multilateral agreements on a national level, or even an international level (Rueter, 2008). Current global stocks of HWPs vary greatly because there is no uniform way of accounting for product life, decay rates, and system boundaries (Pingoud and Lehtila, 2002; Pingoud *et al.*, 2003; Green *et al.*, 2006). There are also little data available on the usage and disposal of HWPs (Kuchli, 2008). In addition, where system boundaries are defined is a contentious issue and opinions are divided. Also, landfills are a topic that should be an important part of this analysis. Their "end-of-life" assumptions are intrinsically linked to assumptions about their effectiveness in methane (CH_4) capture, and this depends on the material composition of a landfill and its design.

Harvested wood products such as solid wood (furniture, construction, flooring), and paper and paperboard can be reservoirs of carbon, but require energy and heat inputs, and their end-of-life pathways can further or

hinder carbon sequestration, depending on management. Even assuming the high end of the estimates, forest products are still a very minor component of the global carbon budget. Manufacturing wood products usually operates on a blend of fossil energy and biomass energy, a byproduct derived from wood waste, and which also reduces emissions by displacing fossil fuel as an energy source. Newer wood products such as oriented strand board, laminated veneer lumber, and I-joists, vary in amounts of energy required for manufacture, and vary between 80 and 220% of the energy needed as compared to solid sawn wood. It is unclear whether the lower density of newer wood product materials, given their increased strength and greater utilization of wood resources, offsets the energy intensity per unit of the newer materials. Paper products contain significantly more embedded fossil fuel (carbon) energy than wood. (Embedded energy, also known as embodied energy, refers to the energy consumed in the prior steps in the product chain.) Currently about 50% of US paper production is manufactured using recycled paper. Recycled feedstock may reduce or increase GHG emissions relative to virgin pulping, depending on the pulping process and energy sources. Global transport of wood and paper products is estimated to account for 27% of total fossil carbon emitted within the manufacturing and distribution process.

Several researchers assert that substitution of wood for other construction materials (e.g., steel and concrete) produces net GHG reductions. These substitution effects may be up to 11 times larger than the total amount of carbon sequestered in forest products annually. Quantification of substitution effects relies on many assumptions about particular counter-factual scenarios, most importantly linkages between increased or decreased forest product consumption and total extent of forestland. The end-of-life pathways of HWPs can augment GHG emissions reductions. Once discarded, HWPs can be burned for energy production, recycled or reused, or put in landfills, where the carbon can remain indefinitely due to anaerobic conditions. Inclusion of end-of-life pathways in HWP carbon stock calculation models is crucial, as failure to do so leads to estimates with a high degree of error.

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Part 6

Silvicultural Applications for Different Land Uses

Examples of silviculture that range from extensive public forestlands to urban environments, and from intensive timber production to watershed management.

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

28

Ecosystem Management: Managing Public Natural Forests for Multiple Values

Introduction

It is estimated that of the 10 billion acres (3.9 billion ha) of forests across the world, over 86% of them are publicly owned (FAO, 2010; PEFC, 2015). Public lands are those lands that are owned by national, state, and regional governments, government-owned institutions (e.g., National Park Service, US Forest Service), or other public entities (e.g., water authorities). Private land is owned by individuals, communities and cooperatives, industries, financial investment funds, conservation organizations and land trusts, private societies, and non-governmental organizations.

Most of these public lands are "owned" by national governments, but in many cases they are also claimed by local communities and indigenous or tribal peoples (White and Martin, 2002). Almost all of the forests that are publicly owned are extensive native forests that are restricted to the more marginal uplands and remote regions of countries. Many are in very poor condition from past exploitation, yet these forests are vital sources of drinking water and irrigation for agriculture. They are usually home to each nation's wildlife and biodiversity, they serve as an important open space for outdoor recreation of various kinds, and they serve as a source of wood and non-wood products. Since the mid-1980s, led chiefly by work in North America, studies and research have built a volume of work demonstrating new ideas about managing forestlands for diverse values, particularly on public lands, through ecosystem management and adaptive learning.

This chapter is organized into three parts. In the first part, regional and national differences in public land ownership across major forested countries of the world are described. This introduction is intended to demonstrate, especially to the North American reader, the overwhelming importance that public forest ownership potentially can play in managing native forests using our current science and thinking of ecosystem management. The second part presents ecosystem management and silvicultural techniques for managing extensive native forests for multiple public benefits. The third part of the chapter describes three regional examples of ecosystem management approaches to silviculture practiced primarily in North America.

Regional and Global Differences in Public Land Ownership

Scandinavia and the US are the only major forested countries with greater amounts of private forest land than public land in the world (Sweden: 24% of forested acres publicly owned; Finland: 32%; and the US: 43%). This is followed by Germany (54% public, 46% private). At a regional scale, North America has the lowest percentage of public land ownership (70%), followed by Australasia/Oceania (76%) and South America (82%). By contrast, the forestland in Europe (including Russia), Asia, and Africa, is all greater than 90% publicly owned (PEFC, 2015) (see also http://rainforests.mongabay.com/deforestation/2000/). However, although the percentage of publicly owned forest acres is lowest in North America, much of the work on adaptive management in recent decades has come from these forests.

The United States and Canada

There are approximately 750 million acres (303 million ha) of forestland in the US, comprising 34% of the country's land base (Butler, 2008; Nelson, Likens, and Butler, 2010) (Fig. 28.1). In the eastern part of the country, 80% of forestland is privately owned (Alvarez, 2007; Butler, 2008), and National Forests represent another 6%. The remaining public lands in the east are owned by states or towns and managed as parks or forests. In the western US, public land ownership represents two-thirds of the forestland (including 47% held as National Forests) while the remainder is private (Alvarez, 2007).

The US has over 150 National Forests covering nearly 200 million acres (81 million ha) (Alvarez, 2007). The land is managed by the US Forest Service, an agency within the Department of Agriculture. The original

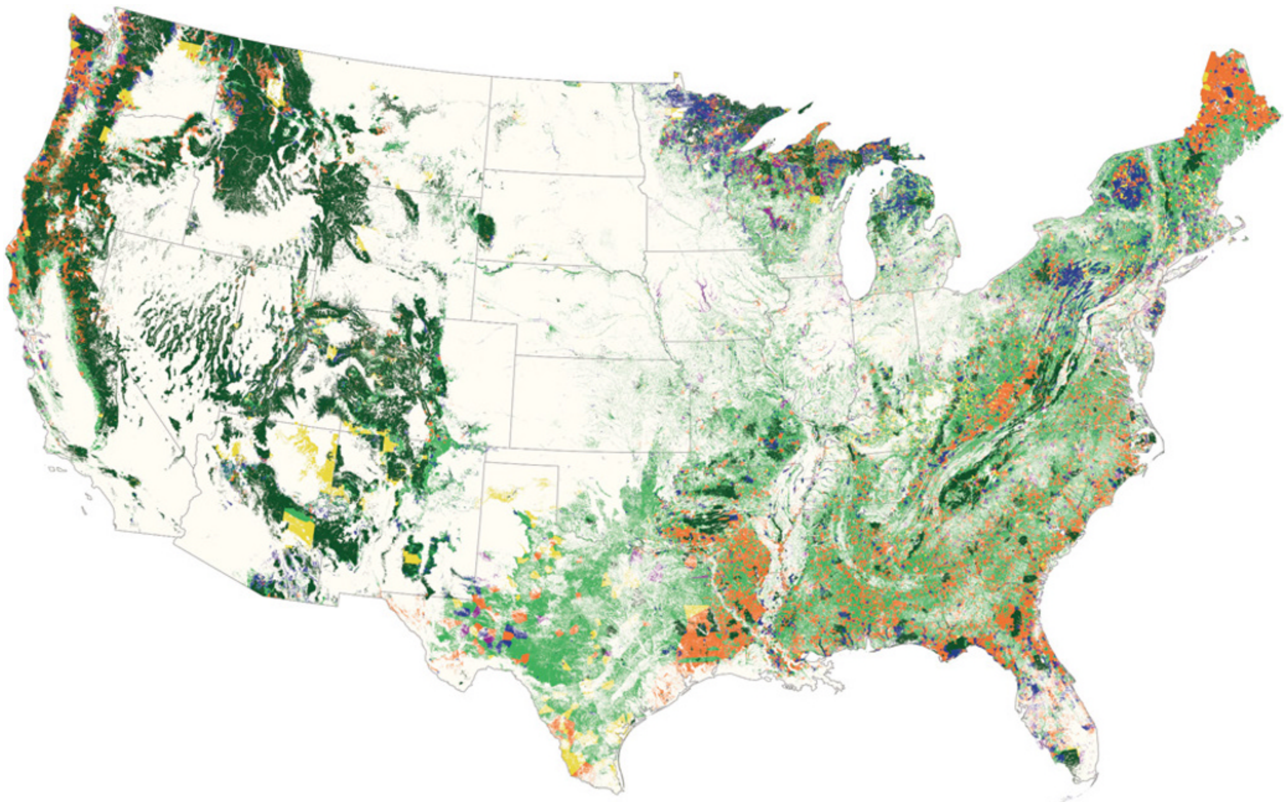

Figure 28.1 Land ownership in the United States. Dark green, federal land; blue, state; purple, local public ownership; pale green, private land; orange, private industrial timber land; yellow, other private land. *Source:* US Forest Service.

management goals when the first lands were acquired in the late 1800s and early 1900s were to serve as a source of wood products for the nation's future development, range for livestock, and as a source of clean water for downstream uses. It was not until the "multiple-use, sustained-yield act" of 1960 that forests were recognized for a broader set of management values and objectives that included outdoor recreation, wildlife and fish, as well as the pre-existing values of timber, range, and watershed protection. Other land uses, such as rights of way for pipe and power lines, public roads, hydropower, and lodging facilities and resorts, were covered by the occupancy and use regulations for national forests under the Organic Act of 1897 (MacCleery, 1993).

Canada has vast and extensive forestland covering 740 million acres (300 million ha), which is about 34% of the land base. Almost all of the forest (94%) is publicly owned, primarily by the Provinces and Territories. Four percent is in Federal ownership and mostly as National Parks, defense land, or lands held in trust for indigenous peoples. Most of the provincial land outside of Provincial Parks is managed using concessions, where the responsibility of carrying out the management of the forest lies with private companies. This is done under license or timber supply agreements where the provincial governments collect royalties and are responsible for monitoring and enforcing the laws.

Europe and Russia

Most of western Europe has little forested land, with the exception of Germany and Scandinavia (Norway, Sweden, and Finland). In Germany, 32% of the land is in forests, about 27 million acres (11 million ha), of which about 56% is managed as public land mostly by the German States. Like many western European countries, nearly half of the forestland is considered plantation, by far the majority on private land. About 50% of the land in public ownership includes State Parks and conservation areas.

In Scandinavia there is considerably more private forestland than public. Sweden has 70% of its land in forests (70 million acres, 28 million ha), of which 24% is public land and 76% is private. A little less than half the public land is in parks and the rest is managed for multiple uses. The majority of the private land is planted for timber production. In Finland, about 73% of the land is forested, 54 million acres (22 million ha). About 32% of that is in public ownership with the remaining land in private hands, and 9% of all forests are in parks

and reserves, while 27% are in plantation. Norway has about 33% of its land base, about 25 million acres (10 million ha), in forest. About 86% of the forestland is in private, and only 14% is in public land ownership. Almost no land is protected specifically as reserves for protection, though many forests are protected for soil and water.

Russia has by far the largest amount of forest cover compared to all other nations with 2 billion acres (800 million ha), or 50% of its land base. Almost all of it is publicly owned and managed by the Ministry of Natural Resources. Most of the timber lands are managed by company concessions, with 42 million acres (17 million ha) of planted forests. Most of the land is managed for multiple purposes.

China and Asia

After Russia, Brazil, Canada, and the United States, China ranks the fifth largest in forestland with 500 million acres (206 million ha) or 22% of the land base. Between 1990 and 2010, the country actually gained 32% in forestland, mostly through reforestation of barren and steep lands. China now has 190 million acres (77 million ha) of plantation, the largest amount in the world. Most of the forestland is publicly owned (68%) with the rest owned privately. A high proportion of the planted forests are for protection of soil and water resources which include over 30% of forestland management objectives, compared with 40% for timber production.

Indonesia has the largest amount of tropical forest remaining in Asia, with 230 million acres (94 million ha) or 52% of the country's land base. Like many tropical countries, 91% of the forestland is government owned and 9% is in private ownership. Most of the production forest, comprising 53% of forest area, is under timber concessions, the remaining land is considered protection forest (25%) or in reserves and national park (16%).

The country with the third largest forest area in Asia is India, in which 170 million acres (68 million ha), 23% of its land base, is in forestland. Over 86% of the forestland is owned by the government, with the rest being private land. Government land takes various forms with some being state forest managed for multiple use and production, or as national parks and wildlife reserves (63%), and other forests being managed for multiple uses by communities (37%).

Latin America

The country with the largest amount of forestland in Latin America is Brazil, with 1.3 billion acres (520 million ha) of forestland, second only in the world to Russia. Forestland includes 62% of the country, 81% of which is public and 19% is private land. Public ownership is very diverse with 37% managed by communities and indigenous peoples. Like Indonesia, 10% of the forest was lost between 1990 and 2010.

Peru and Mexico are the countries with the second and third most forestland in Latin America, with 165 and 160 million acres (67 and 64 million ha) with 53% and 33% of land base respectively. In Peru, 62% of the forestland is publicly owned, 18% is in private ownership, and 20% is classified as indigenous reserves. For Mexico, 70% of the forestland is classified as community owned, and 26% as private.

Managing Complex Large-Scale Forests

Through various interest groups, academia, and national politics, society demands its large more remote forests, particularly in the western world, to be managed for resilience to changes in climate and for a multitude of products and services (Messier, Puetteman, and Coates, 2013). Timber is a component, but not necessarily a major one, and society further demands that it be managed in a way that does not impact the other conservation values. Because of this there has been a movement away from even-aged systems and plantations toward stands and their arrangements within landscapes that are both spatially and temporally more complex in structure and species composition (O'Hara, 1998). This means a greater reliance on natural regeneration methods that are, in themselves, more variable; the inclusion of a greater variety of species; and management approaches that imitate (if not exactly replicate) natural disturbance patterns and processes (Sharitz *et al.*, 1992; Mladenoff and Pastor, 1993; Attiwill, 1994; Messier, Puetteman, and Coates, 2013). This means a greater reliance on foresters who have strong ecological knowledge and the ability to craft flexible and unique silvicultural prescriptions that are sensitive to variability in site, topography underlying hydrology and soils, and interactions with disturbance and climate regimes.

The Ecosystem-Management Paradigm

Researchers have developed conceptual frameworks for managing these kinds of forests that are flexible, incremental in application, and that encourage continued learning through adaptation (Franklin *et al.*, 2002; Millar, Stephenson, and Stephens, 2007; Messier, Puetteman, and Coates, 2013). These ecosystem-management approaches fall into two categories: adaptation strategies to help forest ecosystems accommodate to change; and mitigation strategies that use forests to reduce and moderate ecosystem change. The two types

of approaches can be integrated at a landscape scale by applying them in different but contiguous stands over time.

When designing complex adaptation and mitigation strategies, silvicultural systems must integrate ecological constraints with the social and economic objectives of forest management. This means both a better understanding of and a stricter adherence to imitating natural disturbance regimes and their biological legacies after regeneration harvests, such as leaving live trees (reserves), snags, and coarse woody material behind (Gustafsson, Kouki, and Sverdrup-Thygeson, 2010). To do this, harvest prescriptions need to include complexity of structure and spatial pattern to promote the complete spectrum of developmental processes and successional stages found in long-lived forests and to mimic the role of disturbances in creating structural legacies that become key elements in regenerating stands (Franklin *et al.*, 2002).

Most of the ideas for developing more complex spatial and temporal structures and compositions in forests have been developed in North America and western Europe, where large-scale forests, usually public, have been considerably simplified, with a strong reliance on planting originally for timber. In North America, this has primarily been in boreal Canada on provincial lands (Quebec, Alberta, British Columbia) (Bergeron *et al.*, 1999, 2002; Fenton, Simard, and Bergeron, 2009), and in the Pacific Northwestern United States on Federal and State forests (northern California, Oregon, and Washington) (Franklin *et al.*, 1997, 2002; Franklin and van Pelt, 2004; Puettmann, Coates, and Messier, 2012). In western Europe, much of the work has been done in Scandinavia and Germany, with a focus on smaller-scale applications that can accommodate the constraints of a more heterogeneous and fragmented landscape (Spiecker, 2003; Kuuluvainen, 2009). The two approaches are described in more detail in the following sections.

Concept of Ecosystem Management in North America

The ecosystem-management approach and its accompanying complex silvicultural prescriptions developed in North America in the 1990s. These ideas originated following political conflict over the prior even-aged plantation management regime on US Federal and State lands and on Canadian Provincial lands, which was primarily focused on timber production and sought to eliminate almost all snags and coarse woody material, with the thought that they were extraneous. Science is now demonstrating the importance that these forest structures, and the plant–animal relationships they support, play in the long-term sustainability of a forest resource. In the 1990s, public opinion largely turned against intensive management, plantations, and the simplification of a resource that many people thought should be producing multiple benefits. Conflicts continue, particularly between rural people dependent upon jobs within the timber industry, and urban people who have grown to see the forest as a place for recreation, conservation of wildlife, and preservation and protection for future generations. In addition, a growing body of science has been published demonstrating the roles forests play in maintaining many of the support systems for human well-being and livelihood (e.g., clean air, clean water, repositories of genetic biodiversity).

The ecosystem-management paradigm is being used widely to varying degrees across North America, and one of its main characteristics is a focus on the ecological value of old growth. This is done by preserving any old growth that is still present, and by creating and imitating the structural attributes of old growth in managed production forests, second-growth, and young forests (Bauhus, Puettmann, and Messier, 2009). Structural attributes include old legacy trees, coarse woody material, and snags, but researchers now need to produce some quantitative guidelines to ensure some degree of conformity in meeting old-growth management objectives (Bauhus, Puettmann, and Messier, 2009). Studies have shown that managing for structural attributes of old-growth forests ensures a presence of biodiversity associated with late-successional forests.

While structural complexity is important, studies in North America also recognize the importance of maximizing species composition and indicator species to ensure biodiversity conservation. Methods for promoting biodiversity include: (1) the use of unmanaged reserves within managed landscapes; (2) the protection and/or creation of structure-based indicators (such as legacy trees and snags) within the parts of a landscape that are actively managed: and (3) management techniques that create both connectivity and heterogeneity. These strategies can be applied individually or in combination, at both the stand level (e.g., through structural and composition indicators) and across landscapes (e.g., through reserves, connectivity, heterogeneity). Finally, the technique of adaptive management offers the opportunity to continually test, push, and adopt new approaches to silviculture and management that are successful (Lindenmayer, Franklin, and Fischer, 2006). A summary of North American approaches to ecosystem management has been listed in Table 28.1.

Approaches to Close-to-Nature Forestry in Europe

In western Europe, and particularly in Germany and Scandinavia, researchers studying temperate and boreal forests have been recommending and promoting the implementation of ecosystem management under the name **close-to-nature forestry**. However, unlike in North America, forest managers in western Europe are

Table 28.1 Approaches and considerations to ecosystem management in North America.

Primary socio-economic considerations	
1) Adopt multiple forest management strategies	
2) Manage for multiple socio-economic values (resilience)	
3) Ensure for diversity of markets within each socio-economic value (redundancy) (e.g., multiple species and kinds of wood products)	
4) Adaptive management through learning, taking risk-averse and conservative strategies over risky ones	
Primary ecological considerations	
1) Protect old growth or old-growth structures if present, and in managed forest	
2) Emulate old-growth processes and structures within managed production forests	
3) Create old-growth structures and accelerate emulation of old-growth processes in second-growth forests	
Within stands	
Old-growth structures and composition	**Old-growth processes**
Old legacy trees	Ensuring successional stand developmental phases
Coarse woody debris	Ensuring density-dependent tree mortality
Snags	Facilitating understory reinitiation
Understory late-successional plant indicators	Securing and protecting micro-topographic relief (e.g., windthrow mounds)
Ascendance of late-successional trees into the canopy	Facilitating and accelerating gap initiation
Dieback and crown recession	Facilitating and accelerating vertical canopy stratification
Epiphytes, mosses	Facilitating spatial heterogeneity of stems and herbaceous plants (clumped, open)
Ensuring multiple species within the same functional/successional group (redundancy)	
Ensuring presence of multiple functional/successional groups representing different modes of regeneration (resiliency)	
Across landscapes	
Old-growth structures and composition	**Old-growth processes**
Protecting and creating a connected reserve network	Ensuring stand developmental processes of different phases
Protecting hydrological structures/connectivity (e.g., riparian, wetlands, swamps, vernal pools, seeps)	Working with different rotations and cutting cycles (including long and infinite)

Source: Mark S. Ashton.

dealing with the legacy of centuries of agriculture, soil degradation, and reforestation, with single-species plantations of chiefly two species, Scots pine and Norway spruce, making the idea of imitating attributes of old-growth forests a little distant. Conifers were planted because they are easy to establish in the open in desiccating and hot conditions and infertile soils. These plantations served to help alleviate a wood shortage and to protect surface drinking-water supplies. However, these conifer plantations have decreased biodiversity, encouraged invasives, reduced forest resistance to wind and ice storms, and increased problems with insects and disease. Like North America, European societies are demanding a change from plantation forestry to a management approach that diversifies tree species composition, increases biodiversity, and is more ecologically similar to the original forests that had evolved prior to initial land clearing that coincided with the birth of Neolithic agriculture and subsequent complete denudation from the Industrial Revolution and warfare in the 19th century (Kuuluvainen, 2009).

To accomplish conversion of plantations to meet these objectives, many state forests in Germany and Scandinavia have set standards to create site-adapted, mixed forests, primarily by planting beech and oak seedlings underneath or in gaps of the conifers. German and Scandinavian researchers and foresters focus on non-stand-replacing disturbances and the structural and species composition complexity that is associated with such regimes (Kuuluvainen, 2009).

Regional Examples of Ecosystem Management

Sustainable Forest Management in the Canadian Boreal, Quebec

Historically, boreal forests in the province of Quebec have been managed to fit the efficiencies of harvest operations with straight roads, large landings, and regimented large clearcuts that were shaped for ease of operation. The silviculture was usually applied as even-aged blocks with clearcut and plant regimes that were based on the notion that the forest regenerates almost entirely by lethal, large-scale fires. Although lethal fires can be an important driver of forest disturbance, research has demonstrated that fire, the main disturbance driver, occurs with a large variation in return interval and with varying degrees of scale and severity. Applying equal-sized clearcuts uniformly across the forest is not the best way to imitate historical conditions of the forest.

Silvicultural systems need to be developed that imitate the historical variability of fires at both spatial and temporal scales. This calls for a much more sophisticated silvicultural protocol that needs to be both flexible and adapted to learning by experience. Work by Bergeron and colleagues provides an example of this for the Canadian boreal of Quebec Province (Bergeron and Harvey, 1997; Bergeron *et al.*, 2002; Fenton, Simard, and Bergeron, 2009).

Defining Historical Ranges of Variability in Forest Conditions

To develop the protocol, research was needed to define the ranges of variability that disturbances can achieve across a boreal forest landscape. In a fully regulated forest where all parts of the forest are under management, similar to that of an intensively managed agricultural landscape, the forest is divided equally in area among age class. The average fire return interval is about 100 years; this would mean that the forest area would be divided into equal areas that represent each age class from 1–100, and no over-mature forest would exist (Fig 28.2a). However, no forest is average with little to no variability around that average. In the case of the boreal forest, there is large variability that is not that dissimilar from the theoretical construct of the exponentially decreasing graphic in Fig. 28.2b. In this graphic, there are regions of the forest that can burn at short intervals, and there are other places where fire does not occur for a very long time.

There are different approaches to identifying a more appropriate age-class distribution across a managed boreal landscape than the one that is fully regulated with a fixed rotation age. One approach is to vary rotation lengths, such that there will be areas with shorter, medium, and longer rotation age. The areas under each rotation length can be apportioned across the landscape, relative to the known historical natural disturbance frequency and spatial extent (Fig. 28.2c). Alternatively, instead of creating explicitly even-aged stands of different rotation ages and areas, the age-class structure can be mixed within the stands themselves (Fig. 28.2c). Bergeron *et al.* (2002) recommend that a greater proportion be allocated to even-aged systems (referenced by authors as “clearcutting”), and a smaller proportion be allocated to irregular multi-aged systems that have one dominating age class (“partial cutting”), and a smaller proportion be allocated to all-aged and balanced (“selection system”). The selection system can take on treatments that reflect some structural attributes of old growth. In the boreal, Bergeron *et al.* (2002) report that at least 50% of the forest would be considered mature or old growth.

Developing Complex Silvicultural Systems for the Boreal

In Quebec, the southern boreal is mostly considered mixed wood, consisting of both hardwood tree species (birch and aspen) and conifers (white spruce and balsam fir). Further north, almost 100% of the forest is black spruce. To mimic a disturbance regime that is variable in size and severity, variability in both stand size and structure needs to be taken into account. Fire sizes in the boreal are sometimes difficult to replicate in management because of their enormity. Some stands will be very large and represent a disproportionate amount of the area. Fire records show almost 55% of fires that burned during the study period (1940–1998) were 635–37,000 acres (256–15,000 ha) for the mixed-wood systems as compared to 2300–50,000 acres (950–20,000 ha) for black spruce (Fig. 28.3). There is also little evidence that the fires are clustered but appear to act independently of landscape position, suggesting that management of stands for harvest and regeneration should be dispersed. In addition, studies show that fires themselves vary with high proportions of partial burning and some areas that are completely unburned, although the extent of the fire and the degree of severity also varies by year (Bergeron *et al.*, 2002) (Fig. 28.4). In the boreal of Quebec, preserved islands of trees can make up 5–10% of stand acreage, partially burned areas can be 30–50%, with remaining areas severe enough to be truly lethal. This indicates that management must be flexible, and local conditions must be taken into account when designing spatial variability.

In order to develop the silvicultural systems that Bergeron *et al.* (2002) suggest to create the structural complexity for both mixed-wood and black spruce forest types, the fire-severity regimes described above should be emulated. For mixed-wood early-successional species, paper birch and aspen succeed into the canopy as

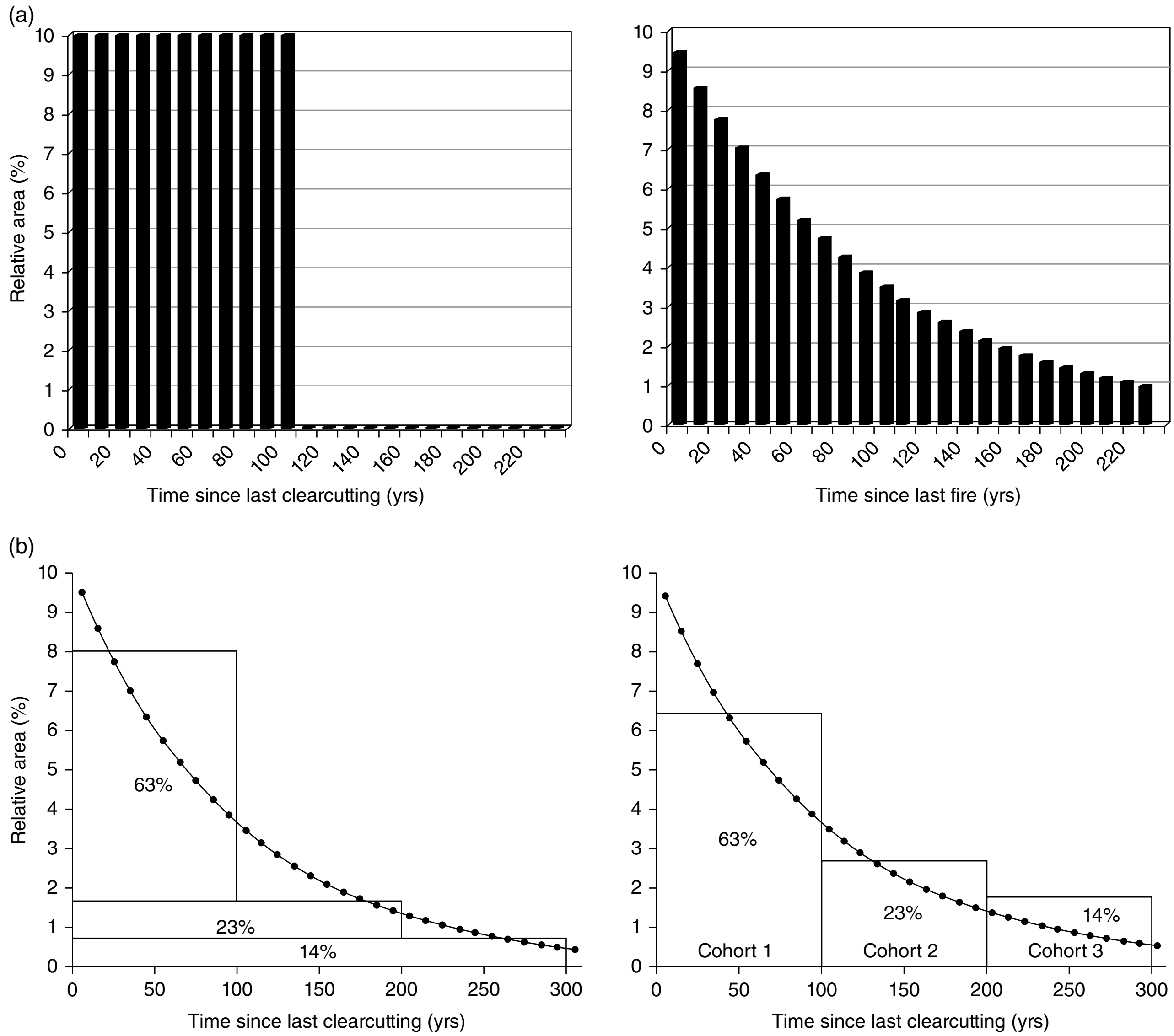

Figure 28.2 **(a)** Left: a fully regulated forest with each age class representing an equal area in a 100-year even-aged rotation, based on a mean fire cycle of 100 years. Right: an example of a fire cycle with mean return interval of 100 years, but with considerable variability across the landscape, with some areas receiving multiple fires at short intervals of time and other areas having fire at much longer intervals. *Source:* Bergeron, 2002. Reproduced with permission from Her Majesty the Queen in Right of Canada on behalf of the Government of Canada, Natural Resources, Canada. **(b)** Left: a strategy to emulate the variability of fire return intervals across the landscape by applying different rotation lengths to areas proportional to the frequency of disturbance (Seymour and Hunter, 1999). Right: an alternative for boreal forest proposed by Bergeron *et al*. (2002), where managed areas are proportionately allocated to different silvicultural treatments through methods of regeneration: Cohort 1 - clearcut (CC), single cohort; Cohort 2 - partial cut (PC), two cohort; Cohort 3 - selection cut (SC), three cohort. *Source:* Adapted from Seymour and Hunter, 1999, in Bergeron, 2002. Reproduced with permission from Natural Resources Canada, Canadian Forest Service, 2017.

pioneers after severe fires, and are eventually replaced by more shade-tolerant conifers such as white spruce and balsam fir. For the even-aged silvicultural system with rotations of 100 years, the best mode of regeneration is to conduct a true clearcut with a prescribed burn, and to either plant or rely upon natural regeneration to seed in, or to use some combination of both. However, these same stands could be regenerated partially with an irregular seed-tree system, leaving structural reserves behind singly or in groups that create a multi-aged stand. These same stands can be maintained in this age-class distribution with the use of irregular systems, potentially supplemented by planting, or can be converted over time to a selection and all-aged management that reflects an old-growth structure and species composition primarily of spruce and fir (Fig. 28.5a).

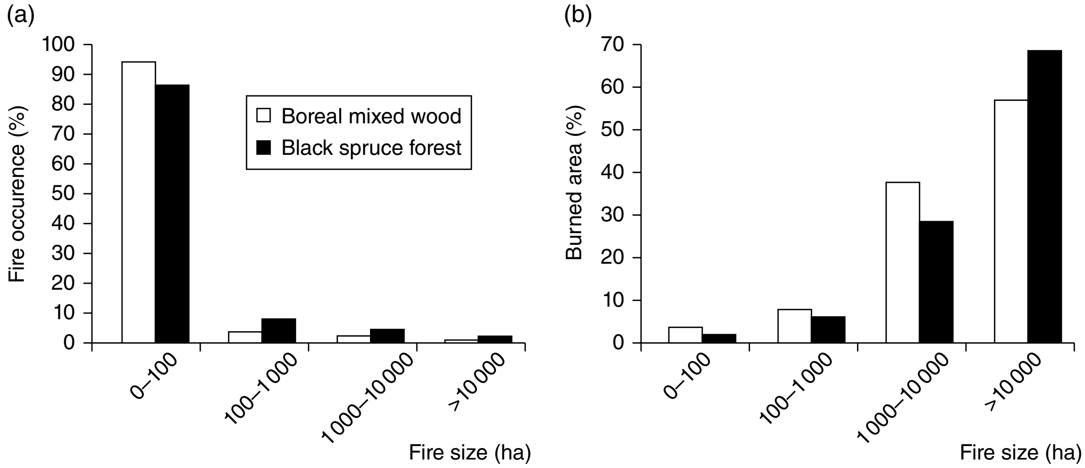

Figure 28.3 **(a)** Relative frequency of fires in the boreal by fire area. **(b)** The relative area burned by each fire size class. *Source:* **(a, b)** Bergeron, 2002. Reproduced with permission from Her Majesty the Queen in Right of Canada on behalf of the Government of Canada, Natural Resources, Canada.

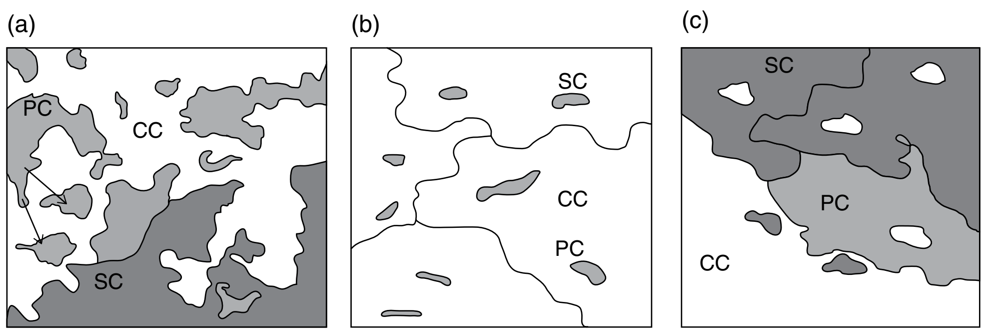

Figure 28.4 Spatial maps depicting time since last fire by three age groupings: younger fires (less than 100 years); medium fires (100–200 years); and older fires (over 200 years). **(a)** A map depicting the natural forest mosaic of times since last fire. **(b)** A map depicting a hypothetical mosaic with a 50–80-year fire return interval. **(c)** A map depicting a hypothetical mosaic under a 300–500-year fire return interval. The letters represent the representative silvicultural treatments if emulating each of the spatial fire maps: CC, clearcut (single-aged); PC, partial cut (irregular system, multi-aged); SC, selection cut (all-aged). *Source:* **(a–c)** Bergeron, 2002. Reproduced with permission from Her Majesty the Queen in Right of Canada on behalf of the Government of Canada, Natural Resources, Canada.

The northern forest type of black spruce regenerates from lethal fire. After establishment, dense even-aged cohorts self-thin to more open forest that comprises the original fire-origin trees and younger individuals that regenerate by layering. Over time, the forest gradually transforms to an all-aged spruce stand. Silvicultural systems can be used to match all three stand development phases in a similar manner to mixed wood (Fig. 28.5b).

Managing for Complexity in the Longleaf Pine Ecosystem, Southeastern United States

The longleaf pine ecosystem of the southeastern US consists of a single dominant tree species that creates a structure and a habitat within which many other species can be found. This forest type dominates the poorer, drier, more acid soils of the coastal plain from North Carolina to East Texas. These soils are typified by the flatwoods of Florida, Georgia, the Gulf states, and the sandhill region of the Carolinas. The ecosystem is driven and governed by recurring frequent surface fires. The ecosystem is highly fragmented and remains mostly restricted to Federal and State lands such as the National Forest system, and to several large private estates.

Studies have demonstrated that the natural disturbance regimes for longleaf pine are extremely varied in frequency and scale, and they include lightning strikes, single tree windthrows, surface fires, tornadoes, and hurricanes (Palik, Mitchell, and Hiers, 2002). The range of disturbance regimes means that changes in forest structure can be very incremental and slow (e.g., windthrow) or sudden and dramatic (e.g., tornado). Baseline natural forest disturbance regimes are thus highly variable (see Table 28.2).

The most important driver of forest change is the incremental effect of lightning strikes. Lightning kills more

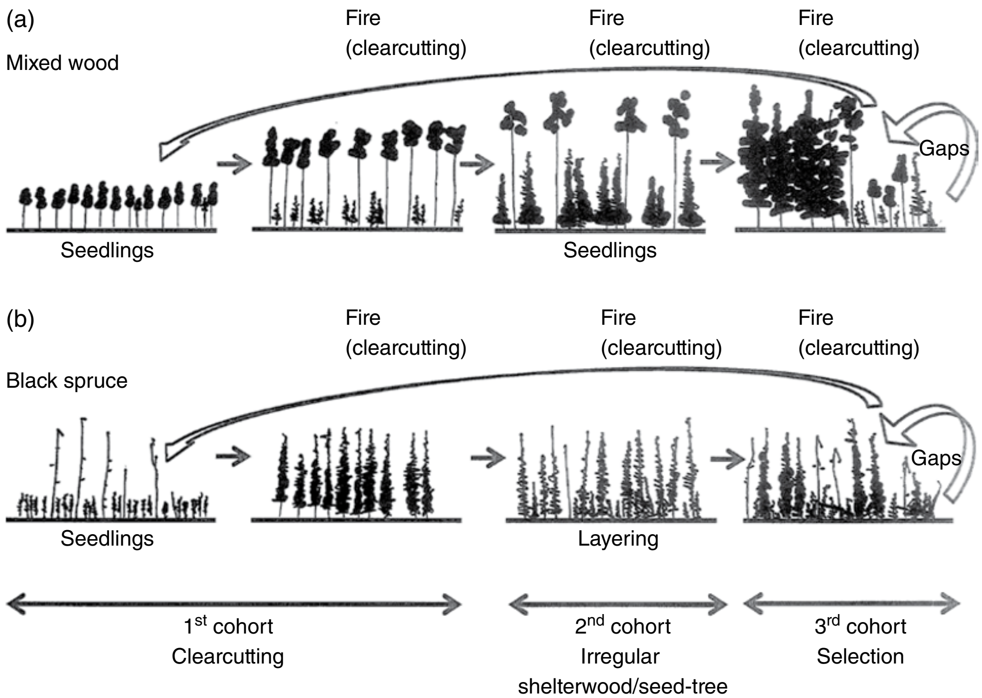

Figure 28.5 Stand dynamics and the silviculture proposed for the boreal forests of Quebec. At any one stage the stand can be regenerated by true clearcutting with an option to plant or to continue to successionally develop. At intermediate stages of multi-aged condition stands can be regenerated by irregular seed tree methods. At all-aged conditions stands can be perpetuated through selection systems. **(a)** The mixed-wood forest. **(b)** The northern black spruce forest. *Source:* **(a, b)** Bergeron, 2002. Reproduced with permission from Her Majesty the Queen in Right of Canada on behalf of the Government of Canada, Natural Resources, Canada.

Table 28.2 Documented natural disturbance regimes that create openings within the canopy of the longleaf pine ecosystem.

Kind of disturbance	Rate of disturbance to create a gap	Size of disturbance
Hurricane[1]	Instantaneous	>2500 acres (1000 ha)
Tornado[1]	Instantaneous	>250 acres (100 ha)
Surface fires[2]	Incremental, decades	<2.5 acres (<1 ha)
Lightning strikes[2]	Incremental, weeks to months	<2.5 acres (<1 ha)
Individual tree windthrow[2]	Incremental, slow, decades to hundreds of years	<2.5 acres (<1 ha)

1) Platt and Rathbun, 1993
2) Palik *et al.*, 1997
Source: Adapted from Palik *et al.*, 2002.

trees than any other disturbance regime, with approximately one tree being killed on 7–20 acres (3–8 ha) per year (Outcalt, 2008). Lightning strikes largely occur in the summer months (June–August) and vary in number by year (Fig. 28.6). The strike probability increases almost linearly as the tree grows in stature (Outcalt, 2008).

Silvicultural Considerations

There are two main operational aspects that all silvicultural systems must accommodate when emulating natural disturbance regimes of longleaf pine ecosystems: fire and gap size. These phenomena drive both the floristics and the ability of pine to establish and replace itself. Both human use of fire in longleaf pine forests and our understanding of its application in these systems have a very checkered past. Pre-European fire regimes were frequent (every 2–10 years) and crept along the surface, mostly originating from dry lightning strikes in the summer. But in the more recent past, it was associated with land clearance and site preparation to convert longleaf lands to plantations of loblolly and slash pine. Managers usually burn in the winter, primarily to create habitat for bobwhite quail. Winter burning is both operationally and logistically easier and less dangerous. Burning in the winter has influenced the floristics and phenology of some plants, but the most critical component is ensuring that there is fire in the first place (Kirkman, Drew, and Edwards, 1998). The greatest change in floristics, and reduction in the uniqueness of the wiregrass–herb composition, occurs when no fires are repeatedly prescribed.

The second silvicultural constraint to account for is the gap size that is necessary to establish longleaf pine. Studies have demonstrated that gaps of at least 0.35 acres (0.14 ha) in size must be made in the canopy to allow

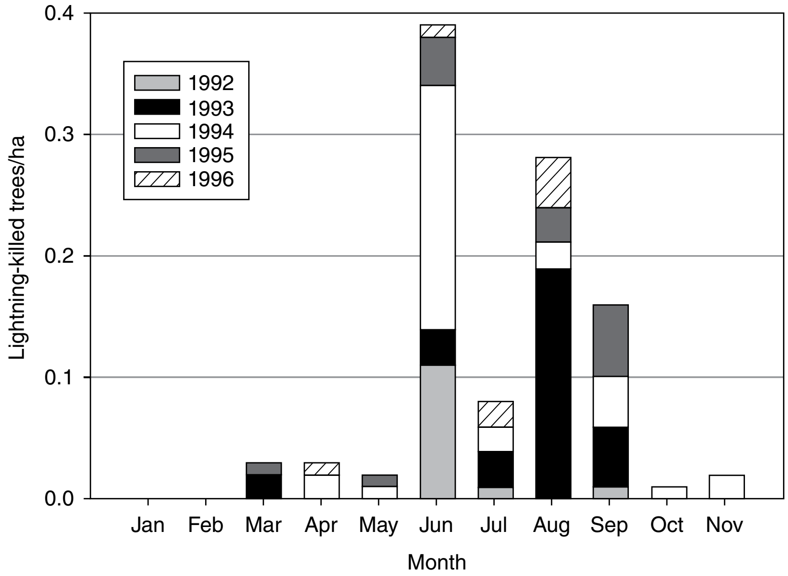

Figure 28.6 Lightning-killed trees by month and year. *Source:* Outcalt, 2008. Reproduced with permission from Elsevier.

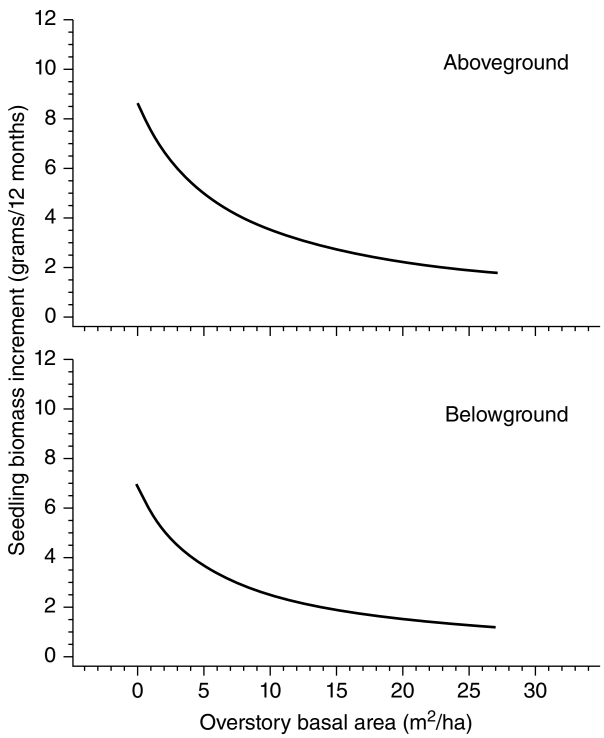

Figure 28.7 Seedling growth as measured by biomass increment both aboveground and belowground in relation to overstory basal area. *Source:* Palik *et al.*, 2002. Reproduced with permission from Elsevier.

pine seedlings to germinate and establish without competition from the larger trees for belowground resources of soil moisture and nutrition. Basal area of the overstory greater than 35 ft^2/acre (8 m^2/ha) generally inhibits regeneration growth (Fig. 28.7). In such cases, the overstory should be variably arranged in denser clumps to accommodate openings. Uniform dispersion of trees in this basal area range or higher will not satisfactorily establish regeneration (Palik, Mitchell, and Hiers, 2002). Keeping overstory basal area below 26 ft^2/acre (6 m^2/ha), and ensuring that some kind of sizable canopy opening is maintained across the stand, is most desirable for moving a stand from single-aged to incrementally multiple-aged, and then all-aged.

Other factors that need to be recognized as operational constraints when trying to emulate natural disturbances within longleaf pine include the recognition that the windthrow pit-and-mound topography can create unique ecological microsites for the herbaceous and wildlife communities, as compared to creating openings by cutting trees and leaving stumps. Finally, because disturbance regimes are so variable in time and space, it is difficult if not impossible to replicate the full range with silviculture, given operational and economic constraints. It is pointless to try to strictly adhere to some of the more difficult components, but recognizing and attempting to emulate, to some degree, the ecology of the longleaf ecosystem is better than nothing.

Silvicultural Pathways

Most longleaf pine is on public forestland in the southeastern US. This land is governed by multiple values and uses, the most important of which are wildlife, biodiversity conservation, and timber. The forester has to develop silvicultural systems that can accommodate both the diversity of human values and the diversity of natural disturbance regimes that maintain the longleaf pine ecosystem. A range of silvicultural options is available. Palik, Mitchell, and Hiers (2002) provide four examples that capture this range when converting even-aged longleaf stands to multiple- or all-aged stands for

timber harvesting and increasing wildlife and vegetation diversity.

1) The first example is the simplest: move the stand to a two-age (two-cohort) system through the irregular seed-tree regeneration method, retaining an overstory basal area of about 26 ft^2/acre (6 m^2/ha). Some degree of site scarification maybe necessary to eliminate below-ground competition where regeneration establishment is desired. This is the easiest treatment to promote more structural complexity than a single-aged stand. The drawback, if timber is of importance, is loss of growth to the overstory to ensure recruitment beneath (see Chapter 11).
2) The arrangement could be made more structurally and spatially complex by clumping and varying the tree density to 26–44 ft^2/acre (6–10 m^2/ha). This would allow more overstory basal area to be retained. This kind of treatment would be called an irregular shelterwood that would initially promote a second age class, but with time a third age-class could develop with the further removal of some of the older clumps to make new gaps. In the end, there might be three relatively spatially explicit age classes with trees attaining maturity for harvest at about 70–80 years. A variant might also include holding onto a few individuals of the mature age class to keep as the oldest reserves for another rotation.
3) To progress further and create an all-aged stand, the stand would be managed using a single-tree, group, or hybrid system of regeneration. Gaps would be created in the first cutting cycle that would be further enlarged in the second cycle. The method is obviously more iterative and would take a longer time to accomplish structural complexity, as compared to the irregular seed-tree and shelterwood methods. However, the structure would eventually be more uneven, clumpier, with a greater diversity of age classes than the prior two methods.
4) Finally, the closest harvest treatment to simulating old-growth development is to let the stand become overmature on its own and to harvest only those trees that die from lightning strikes and windthrow. This is obviously the least intensive and longest method to achieving an old-growth structure. The value of the trees harvested would be much higher because of a higher proportion of precious heartwood within the tree bole, but this would not make up for the loss in yield. However, this would be the closest to emulating the natural processes of stand development.

In all these examples, fire should be used frequently (1–10 years) as prescribed surface burns. Most can be done in the winter but when done during a regeneration treatment, an opportunity to burn in the summer (lightning season burning) should be taken if conditions are suitable. Managing across forest landscapes that are already fragmented, as are the public forests of the southeastern US, can be complex. One solution is to take the triad approach of allocating different parts of the forest landscape and their associated stands to more intensive and simpler two-aged irregular seed-tree systems in one area, less intensive selection in another area, and irregular shelterwood systems to other areas, all of which are embedded within a reserve system (Hunter *et al*., 1996; Seymour and Hunter, 1992). In doing this, the lessons learned by careful monitoring can allow the forester to adjust and adapt treatments, as a better understanding of the longleaf pine ecosystem becomes apparent.

Managing Ponderosa Pine for a Pre-European Landscape in the United States Southwest

The forests of the southwestern US are dominated by ponderosa pine, a tree species with a wide range across most of the western US and into interior British Columbia. A history of forest clearance for sheep grazing, logging for timber, a policy of fire protection, climate change, and invasive exotics, have all coalesced to create forest conditions that are very different from the time when the first settlers arrived (Covington and Moore, 1994; Veblen, Kitzberger, and Donnegan, 2000). There is now debate about the restoration of this forest type to a former structure and ecology that existed over 100 years ago (Allen *et al*., 2002). The objective of this restoration agenda is to create a more resilient forest that is more capable of adapting to changes in climate, and that can accommodate future socio-economic values, particularly on Federal Lands of the National Forest Service and the Bureau of Land Management. Researchers have proposed, and in places embarked upon, changing the existing dynamic of these forests using baseline ecological research (Covington and Moore, 1994; Fule, Covington, and Moore, 1997; Allen *et al*., 2002).

Disturbance

Many studies have demonstrated that ponderosa pine ecosystems of the southwestern US are driven and formed by frequent ground fires, although fire frequency can vary with elevation. These fires were tied both directly and indirectly to changes and supra-annual oscillations in climate, especially droughts, and to secondary stressors such as insect outbreaks (Veblen, Kitzberger, and Donnegan, 2000). Regeneration was associated with periods when fires and mast years were followed by wet years (Allen and Breshears, 1998; Swetnam and Betancourt, 1998; League and Veblen, 2006). All of this made for a varied spatial and temporal landscape for ponderosa pine dynamics, recruitment, and structure, and suggests that species composition, stand densities, and basal areas all varied across the landscape (Collins, Omi, and Chapman, 2006; Brown *et al*., 2015).

Baseline studies suggest that mean fire return intervals prior to European settlement varied across this region from every 4 years to over 30 years (Swetnam and Baisan, 1996). Densities of trees with boles greater than 12 in (30 cm) DBH varied from 8–50 trees/acre (19–126 trees/ha) (Woolsey, 1911). However, because of supra-annual wet periods, and a fire-exclusion policy by the State and National Forest Service since the 1950s, recruitment of dense regeneration of shade-tolerant fire-prone spruce, Douglas-fir, and true firs, has occurred at higher elevations of the ponderosa pine range. At the lower elevation range of ponderosa pine, fire-sensitive pinyon pine and juniper in-growth has occurred. Stand densities of trees over 12 in (30 cm) are now often over 1000 trees/acre (400/ha) (Allen, 1998).

Silvicultural Treatments

Allen *et al.* (2002) summarize the following silvicultural treatments to recreate the same kind of spatial and temporal variability of ponderosa pine as recorded in pre-fire-protection years.

1) Reducing the risk of severe crown fire is the first priority. The only logical and operationally feasible treatment is to reduce the stem density using intensive low thinnings and variable-density thinnings. The woody debris can be chipped and scattered, piled and burned in the early spring, or removed off site as a product. All of this can potentially alter site conditions (Waltz *et al.*, 2003; Gundale *et al.*, 2005; Skov, Kolbe, and Wallin, 2005). Trying to reintroduce surface fires when and where possible would be the most expedient and appropriate, but this can be logistically difficult.
2) To accomplish this, areas of high risk because of forest structure and mortality conditions need to be treated first. Other areas that need to be identified and either protected or treated are ecologically important and sensitive sites (e.g., old growth, wildlife wintering grounds), and areas that are adjacent to houses and towns.
3) Identify and protect reference sites that are thought to reflect historical stand conditions such that data on spatial and age-class distributions of the stand can be compared and contrasted with treatment areas. Objectives should be focused on creating a more resilient stand and landscape that is functionally dynamic and represents the successional integrity of stand dynamics for ponderosa pine, rather than actual stand numbers, age-class distributions, and size classes.
4) Start with a more conservative approach with multiple treatments that can be monitored and evaluated through an adaptive learning process. More aggressive treatments may need to be done in high-risk areas.
5) Identify and work with existing forest structures that can more quickly facilitate stand characteristics and attributes that represent the original older forest, large trees, and groups of trees. Seek to preserve the large, old, and legacy trees, especially those that were present prior to European settlement. Recommended sizes are 16 in (40 cm) DBH and greater, as well as trees with morphological old-growth attributes (yellow bark, flattened tops, and twisted trunks and branches) (Brown *et al.*, 2015).
6) Take advantage of masting and seasonal wet monsoonal years to recruit pine through irregular seed-tree and group selection methods of reproduction. Take advantage of pulses of regeneration that promote recruitment over a period of 10 years, and then cease for 30–50 years (League and Veblen, 2006).
7) Facilitate landscape-level heterogeneity by allowing fires, droughts, and insect outbreaks (and their combinations) to reform and conform to hydrology, landform, and soil variability post mechanical treatment. This can be allowed through more passive approaches that accommodate patchiness and mortality, and their associated patterns with supra-annual El Niño–Southern Oscillation (ENSO) events (Kitzberger *et al.*, 2007; Sheriff and Veblen, 2008)
8) Regulate grazing from livestock carefully with rotations to protect the diversity of understory grasses and shrubs.

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29

Application of Silviculture to Watershed Management

Tall forests grow where there is plenty of water, and most of the fresh water of streams and lakes runs off of lands that are forested or are capable of supporting forests. The quantity and quality of water that flows from forests are always important considerations for silviculture, regardless of whether the water is used by people or by fish or other aquatic organisms. Public policy often requires that forest owners pay attention to watershed management even if they do not use the water themselves. The best kind of watershed cover is forest. Fortunately, well-conducted forestry is compatible with watershed management more than any other land use. Many forests are created or maintained for the primary purpose of watershed protection and management, and forests are the chief sources of water for vast metropolitan areas and agricultural irrigation. Many of these forests are managed expressly for this purpose, and foresters who manage this land use silviculture to achieve their water-quality and water-regulation goals.

Introduction

The long-term watershed studies conducted on the US National Forests starting in the 1950s are some of the most comprehensive ecological investigations in the world on the effects that forests have on water yield and water quality. They have been summarized in many reviews over the last 20 years (Bosch and Hewlett, 1982; Swank and Crossley, 1988; Brown and Binkley, 1994; Hornbeck *et al*., 1996; Likens and Bormann, 1995; Stednick, 1996; Hornbeck, Martin, and Eager, 1997; Swank, Vose, and Eliot, 2001; de la Cretaz and Barten, 2007; Jones and Grant, 2010). Most of these reviews are based on the numerous paired watershed catchment studies that have been done across different forest biomes of the US National Forest System (Fig. 29.1).

The forestry aspects of watershed management have been thoroughly reviewed by Satterlund and Adams (1992), and Riedl and Zachar (1984). The standard objectives of silviculture in regard to water management are erosion control and moderation of the extremes of stream discharge. Sometimes the purpose of the forest is to increase the supply of usable water or improve its quality. However, avoiding damage to forested watersheds is much more a matter of proper management of roads and trails than of modifying silvicultural treatments within the forest itself. The abilities of trees and forests to protect and regulate watersheds and runoff are likely to become much more important, as society recognizes their service values for urban runoff, coastal and riparian flood control, and drinking water supplies (Alcott, Ashton, and Gentry, 2012).

This chapter explains the silvicultural and ecological principles related to the issues dealing with water. The chapter chiefly covers the silvicultural techniques of managing and regulating for water quality and quantity in forestlands and their silvicultural applications. First, a summary is provided of the studies that were largely done from the 1950s to the 1980s on the biogeochemistry of upland forested watersheds in the US. This research provided the baseline hydrological flows and the erosional and weathering processes of undisturbed watersheds. A forester needs to understand the baseline hydrology and biogeochemistry of a forested ecosystem, and then connect this to the geology, topography, and climate that make every watershed unique. Baseline flows and biogeochemistry of a watershed can serve as a comparison to regional impacts on water quality and regulation. Second, the experimental work of these studies that monitored the effects of intensive land clearance, conversion, and reforestation on water quality and quantity are summarized. Third, the experimental work on effects of various silvicultural treatments on hydrology are reviewed (e.g., clearcutting, thinnings). This knowledge presents and provides different silvicultural treatments for provision of: (a) water quality, and (b) improvement of water regulation and yield. Finally, examples are provided for the use and treatments of vegetation within agricultural landscapes for regulating water quality.

An important resource issue concerning the use of silviculture that is not reviewed is that of coastal and river flooding, and the erosion processes associated with these

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

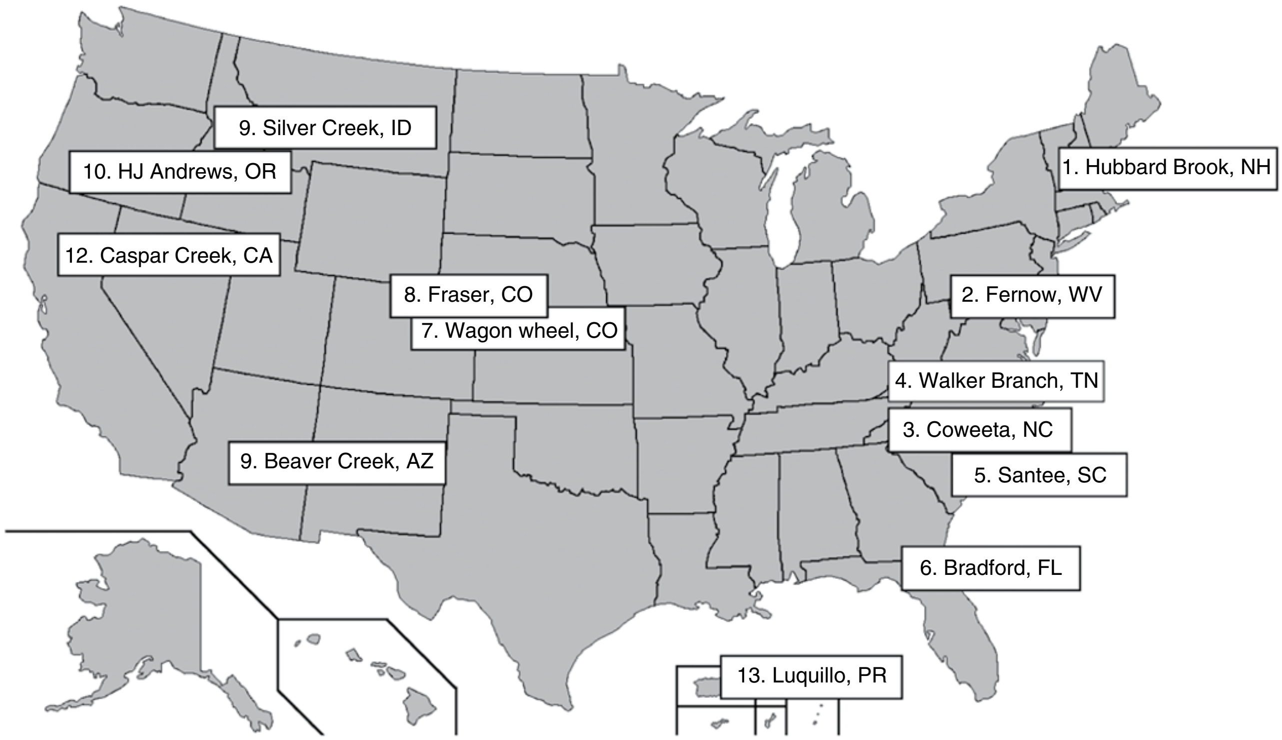


Figure 29.1 A map of the United States depicting the locations of the long-term watershed research sites within the National Forest System. *Source:* Mark S. Ashton.

events. There are several recommended handbooks on the management of vegetation for flood mitigation and erosion control (Clark, 1996; Gray and Sotir, 1996; Salm, Clark, and Siirila, 2000).

Baseline Watershed Conditions

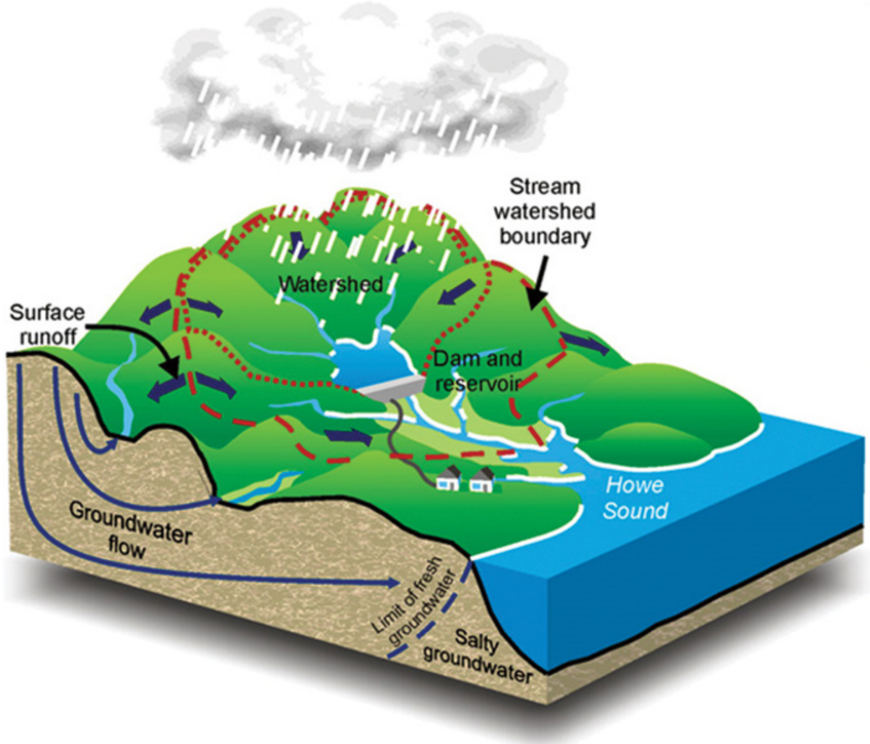
Large-Scale Effects of Forests: Defining and Comparing Watersheds

There are some fundamental considerations to recognize when dealing with the kinds of baseline controls in an undisturbed forested watershed. They can be used to judge which watersheds are polluted or impacted, and to what degree, as compared to those that are not. A **watershed** is an area of land where all inputs ultimately drain to the same point. Watersheds are generally delineated from a point on a stream or river. The inputs include precipitation from the atmosphere and deposition of soil nutrients weathered from the rocks. They are either taken up and stored by the soil or vegetation, or moved through the area with the flow of water that drains from it. Water flows by gravity to the lowest point at the end of the outlet, where all water and nutrients that are lost from the watershed area can be measured as outputs (Fig. 29.2). The outputs include the excess water that "leaks" from the system, along with the sediments and nutrients that are transported with stream water. Careful measurements of inputs and outputs from the watersheds are taken, and all of the classic watershed ecosystem ecology studies have followed this method.

Three factors need to be considered in order to understand the baseline flows and the use-efficiencies of water, nutrients, and pollutants within a watershed. These factors include: (1) natural background inputs from geology, (2) forest history and stand development, and (3) climate and its effects on inputs and on the ecosystem-level processes of the forest itself. Characterizing the natural or background inputs of weatherable nutrients from the ground is the first component of understanding a healthy watershed (Table 29.1). Some of the main inputs to measure are phosphorus, calcium, and potassium, which are key nutrients for soils and drivers of vegetation productivity, but are also pollutants downstream in aquatic systems that can negatively affect human health. Watersheds from different geologies reflect very different background inputs and outputs. Nutrient-rich geologies (e.g., basalts) have inherently higher amounts of nutrients stored in the mineral soil than in the vegetation, while nutrient-poor geologies (e.g., sandstone, granite) will have disproportionately higher amounts stored in the living vegetation and much lower absolute amounts in the soil (Table 29.1).

The second factor to understand is the forest history and the ability of the forest to either take up and store,

(a)



(b)

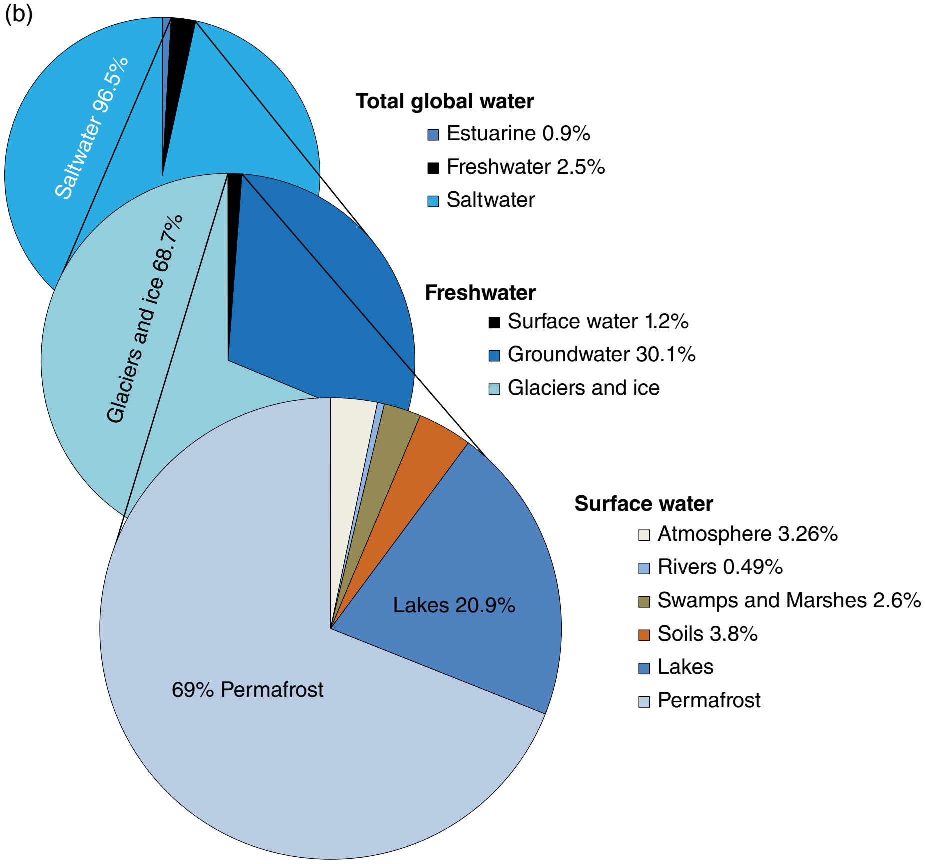


Figure 29.2 **(a)** A depiction of a watershed. The red dashed line defines the watershed boundary within which all water flows downhill toward the stream, river, or reservoir. *Source:* Data from Canada Natural Resources website. **(b)** A summary set of pie charts illustrating where the world's freshwater is located. Only a very small amount can be considered surface water, which is managed for irrigation and drinking water. *Source:* Adapted from US Geological Survey.

Table 29.1 (a) A comparison of the nutrient inputs in precipitation and outputs from streamflow of four watershed ecosystems in different physiographic regions of the US (modified after Swank and Crossley, 1988). Nutrients measured in kg/ha/yr. Walker Branch includes second-growth Appalachian hardwood forest on limestone in a warm temperate climate; Coweeta includes second-growth Appalachian hardwood forest on sedimentary shales and sandstones in a warm temperate climate; Hubbard Brook is second-growth northern hardwood forest on nutrient-poor granite in a cold temperate climate; and H.J. Andrews includes old-growth Douglas-fir/western hemlock forest on the west side of the Cascades on nutrient-rich andisols of volcanic origin in a cold temperate climate.
(b) Summary pools of nutrients above- and belowground for the four forest watershed ecosystems from contrasting physiographic regions. Nutrients in kg/ha.

(a)

	Organic N			Inorganic N			Ca			K		
	Input	Output	Net	Input	Output	Net	Input	Output	Net	Input	Output	Net
Walker Branch, TN	3.6	1.6	+2.1	9.3	1.5	+7.8	12.0	148.0	−136.0	3.0	7.0	−4.0
Coweeta, NC	4.3	3.1	+1.2	4.5	0.1	+4.4	4.8	7.7	−2.9	2.1	5.6	−3.5
Hubbard Brook, NH	–	–	–	6.5	3.9	+2.6	2.2	13.7	−11.5	0.9	1.9	−1.0
H. J. Andrews, OR	1.5	1.8	−0.3	0.7	0.1	+0.6	2.3	50.3	−48.0	0.1	2.2	−2.1

(b)

NITROGEN	Vegetation above and belowground	Forest floor	Mineral soil exchangeable	Mineral soil total	Percentage of nutrients in vegetation
Walker Branch, TN	470	310	75	4,700	8.4
Coweeta, NC	995	140	117	6,800	12.4
Hubbard Brook, NH	532	1,256	26	4,890	8.0
H.J. Andrews, OR	560	740	5	4,500	9.6
CALCIUM	**Vegetation above and belowground**	**Forest floor**	**Mineral soil exchangeable**	**Mineral soil total**	**Percentage of nutrients in vegetation**
Walker Branch, TN	980	430	710	3,800	16.6
Coweeta, NC	830	130	940	2,500	18.9
Hubbard Brook, NH	484	372	510	9,600	4.4
H.J. Andrews, OR	750	570	4,450	–	–
POTASSIUM	**Vegetation above and belowground**	**Forest floor**	**Mineral soil exchangeable**	**Mineral soil total**	**Percentage of nutrients in vegetation**
Walker Branch, TN	340	20	170	38,000	0.9
Coweeta, NC	400	20	510	124,000	0.3
Hubbard Brook, NH	218	66	–	–	–
H.J. Andrews, OR	360	90	860	–	–

Source: (a, b) Adapted from Swank and Crossley, 1988.

or lose nutrients (and pollutants), depending upon its developmental age. Regrowth and second-growth forests sequester a relatively high flux of nutrients, but as forests slow in growth and become more decadent, there is a closer balance between nutrient uptake and loss and a closer balance between processes of biomass decomposition and aggradation. Older systems become more "leaky", losing as many nutrients as the amounts that enter. Initiation and stem-exclusion phases of stand development are aggradation processes that can efficiently sequester nutrients and pollutants. Understory initiation and particularly old-growth forests are more weakly aggrading phases of development, resulting in decreased efficiencies in nutrient uptake and accumulation.

The last factor concerns the nature of climate and how climate affects where nutrients (and pollutants) tend to be stored. For example, northern moist climates with cold winters and short growing seasons promote many

of the "inputs" to be stored in the non-living organic matter of the soil that aggrades under such conditions. In warmer climates, with fast rates of decomposition and long growing seasons, a disproportionate amount of nutrients (and pollutants) can be taken up and stored in the living vegetation.

Small-Scale Effects of Forests: Protecting Soil and Water Quality

Forest vegetation protects soil and water by shedding leaves and other organic structures (twigs, branches) that feed soil organisms (earthworms, ants) and microorganisms (fungi, bacteria), which churn the soil and keep it porous. Litter also protects the mineral soil from the impact of falling raindrops, and it facilitates infiltration of water into the soil, preventing it from running over the surface, picking up solid materials in the process of surface erosion. Much of the water that sinks into the soil emerges later as springs.

Erosion is a natural phenomenon by which land is continually worn down; it cannot be prevented completely. Most erosion of mineral materials in natural forests originates from concentrated overland flow, cutting into the beds and banks of streams during times of heavy runoff. It is very important to maintain or augment the networks of roots of woody plants along the banks of streams in order to reduce or prevent undercutting. What actually moves in water through forest soils on its way to streams is limited to dissolved substances and some particles of clay or very fine organic matter. However, various disturbances can induce *accelerated* erosion of coarser materials, and this is what needs to be controlled in silvicultural practice.

Porous soils are not only resistant to erosion but they also have substantial capacity to detain water temporarily in the larger pore spaces. Water in **detention storage** within soils is ultimately released to streams, but any delay has the virtue of making the streamflow and water supply more even throughout the year. Forests increase the detention storage compared to non-forest land uses, due to the depth of the roots that promote deep water channelization and contribution to deep soil organic matter. Every unit of soil also has capacity for **retention storage** in pore spaces so small that water cannot flow out of them; it can only evaporate or be taken up by plants. Water will not start flowing to streams until the capacities of both detention and retention storage are filled.

The cutting of trees by itself does not impair the porosity and infiltration capacity of the soil, provided that the supply of organic matter (e.g., slash, leaf litter) continues to the soil organisms. Porosity may diminish slowly if the supply of new organic matter is halted, but this will not happen if vegetation regrows. The soil organisms that feed on forest litter are usually much more effective than plows or similar mechanical equipment in keeping the soil loose and porous. Furthermore, they do not have wheels or hooves that compact the soil. With land conversion from forest to non-forest, macropore space declines with the loss of deep rooting and the decline in mineral soil organic matter.

Silvicultural regeneration cutting is aimed at establishing new vegetation and not at preventing it. Forest vegetation of almost any kind will produce organic matter and maintain soil porosity, regardless of whether it is the species envisioned in the regeneration cutting. However, actions that scrape, gouge, or pack the mineral soil and litter layers do impair the infiltration capacity. As described in Chapter 7 (Site treatments), these actions, particularly scraping, can also reduce the supply of chemical nutrients in the soil.

The areas within a stand that are most crucial for watershed management are the **source areas** where soils are so saturated that water can flow from them beneath, or even on top of, the soil surface as seeps and springs. Most source areas are not permanent. After heavy rains or the melting of deep snows, almost all soils are source areas. However, gravity soon removes all the water that is loosely held by the soil, allowing most of it to flow; transpiration from vegetation further dries the soil. The only areas that are permanent source areas are likely to be found along streams, at the bottoms of slopes, and in other places where water collects, or where groundwater provides baseflow during dry periods. Such places are usually indicated by site indicator shrub and herbaceous species.

When a source area functions to yield water, it is also sensitive to compaction or surface erosion. This is because when soil is wet, it lacks cohesion and is prone to compaction by heavy equipment. A major portion of the soil and water damage associated with harvesting and other uses of forests comes from damage to the source areas while they are saturated.

Paired Watershed Studies: Impacts of Land Clearance and Forest Disturbance

Effects of Cutting Trees

There is a deeply rooted yet erroneous popular myth that trees makes it rain and that cutting them causes drastic alternations between drought and flood. The water that falls from the sky comes mostly from air that has been moistened over warm oceans and is lifted by convection over warm surfaces or over mountains and cold air masses. Transpiration from forests by itself rarely moistens air masses enough to make it rain, unless there are very large expanses of forest such as the Amazon. There are data to suggest that local convectional thunderstorms are regional sources of water that have been transpired from the forest elsewhere. This can be an important source of precipitation, particularly during the dry season. Models predict that the complete land clearance of the Amazon for crop cultivation would decrease precipitation during critical periods and increase surface

temperatures. In most circumstances, forests are an effect of abundant precipitation rather than the cause of it. In the vast majority of cases, the cutting of living trees by reducing losses of water to transpiration and interception actually *increases* the amount of water that reaches streams. The myth probably originated from the observation that true deforestation associated with agriculture or grazing often causes rain to run off so quickly from compact soils, that streams flood and then dry up.

The same exposure to sun and moving air that makes tree leaves so efficient at changing carbon dioxide and water to sugar also causes them to transpire large quantities of water back into the atmosphere. Trees also intercept appreciable amounts of precipitation when rain or snow collects on leaves and branches of trees. Some of this precipitation is detained temporarily before falling to the forest floor, but much of it is directly evaporated into the atmosphere. Water losses from transpiration are generally more significant than those from interception and evaporation. Both kinds of losses reduce the amount of water that reaches soil, groundwater, and streams.

Results from Paired Watershed Treatments: Water Yields from Forest Removal

Paired watershed experiments consist of areas of similar size and area that are monitored for water chemistry and flow rates. One area is treated while the other area acts as a control for comparison. An analysis of all the paired watershed treatment studies that monitored the effects of cutting trees on water yield throughout North America showed that, on average, 20% of cover has to be removed in order to produce a measurable increase in streamflow (Stednick, 1996). Cutting has the most accentuated effects in the Intermountain Regions of the west, a region with steep topography and strongly seasonal climate. In this case, removing as little as 15% of the forest cover started to increase water yields downstream. However, in other regions such as in the Great Plains, with its flat topography and thick prairie grass and forb cover, almost 50% of the riparian and woodland cover had to be removed before measurable increases in streamflow could be detected (Stednick, 1996).

In a global study by Bosch and Hewlett (1982), the approximate magnitude of change in increased water yield was estimated by modeling data from watershed studies. Pine and eucalypt forest types cause an average change of about 1.5 in (40 mm) in increased water yield over base flows per 10% reduction in cover. Deciduous hardwood and early successional regrowth cause changes of 1 in (25 mm) and 0.4 in (10 mm), respectively, per 10% reduction in cover. Maximum changes of about 25 in (660 mm) were observed from complete deforestation, as compared to base flow, in a temperate, moist, forested catchment in the Coweeta watershed study, North Carolina (Bosch and Hewlett, 1982).

Studies that compared the nature of deforestation across treated watersheds are best exemplified by work done at Hubbard Brook, New Hampshire (Hornbeck *et al*., 1996; Hornbeck, Martin, and Eagar, 1997), and Coweeta, North Carolina (Swank and Crossley, 1988; Swank, Vose, and Eliot, 2001) (Box 29.1). Findings in the Coweeta study

Box 29.1 A summary of effects of water yield and quality with forest cutting in the deciduous second-growth forests of eastern North America.

Many studies have illustrated the importance and role that vegetation plays when a watershed is cleared. The most dramatic example is that of the Hubbard Brook experiments in the New Hampshire White Mountains, where a watershed was completely deforested and then herbicide was applied as a broadcast application for 3 consecutive years (see Table 1). Large amounts of calcium, potassium, nitrate, and sediment were exported from the watershed as compared to a forested control. A similar study completed at the Coweeta Experimental Watershed in the Smoky Mountains of North Carolina showed results that were completely different when a watershed was completely deforested but no herbicide was applied, and instead, vegetation was allowed to come back. The results illustrate how much of a role that vegetation can play (Table 2). When vegetation is allowed to come back or be released at the groundstory after land clearance, there is a great decline in the amounts of nitrate (600 kg/ha lost per year as compared to 1.27 kg/ha), potassium (38 kg/ha versus 2.17 kg/ha), and calcium (90 kg/ha versus 3.41 kg/ha) that is lost from the watershed, as compared to when the vegetation is prevented from coming back. The marked difference between Hubbard Brook and Coweeta is that vegetation provided shade to the ground, reducing temperatures and decomposition rates, protecting the surface organic layer of the soil from the elements, and creating a fibrous surface root system that takes up nutrients and traps sediments that would otherwise be lost. After deforestation, if vegetation is allowed to come back, it will do so quickly from a variety of regeneration modes (Fig. 1). In moist forests, the initial growing space occupied by advance regeneration can play a disproportionately important role in the first year before early successional pioneers of seed origin take hold. Thus, the lesson is that when practicing regeneration methods (natural or plantings), it is essential to ensure that vegetation is present beforehand or will quickly come in afterwards to ensure maximum soil nutrient and sediment retention. Broadcast applications of herbicide must be used with caution or avoided as much as possible.

Box 29.1 (Continued)

Box 29.1 Table 1 Export patterns of dissolved nutrients and sediment from the Hubbard Brook experiment that deforested a complete watershed catchment followed by 3 years of herbicide application.

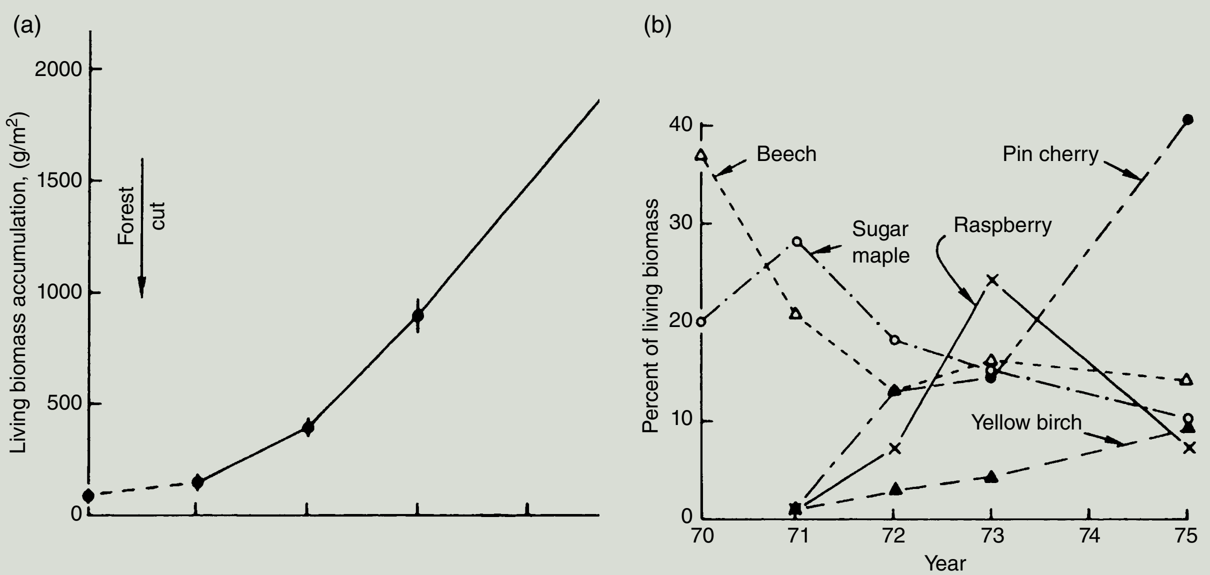
Year after treatment (May–April water year)	Particulate matter (kg/ha)	NO_3^-N (kg/ha)	K (kg/ha)	Ca (kg/ha)
1 pre-treatment	2.8	0.00	0.05	5.00
2 herbicide	90.0	425.00	23.00	85.00
3 herbicide	100.0	600.00	38.00	90.00
4 herbicide	200.0	430.00	32.00	70.00
5 post-treatment	390.0	400.00	30.00	65.00
6 post-treatment	100.0	180.00	15.00	40.00
7 post-treatment	4.0	0.03	4.00	7.00

Source: Data from Bormann and Likens, 1979 and 2012.

Box 29.1 Table 2 Export patterns of dissolved nutrients and sediment from the Coweeta Watershed deforestation experiment for a complete watershed catchment, where vegetation was allowed to come back immediately.

Year after treatment (May–April water year)	Flow (cm)	NO_3^-N (kg/ha)	K (kg/ha)	Ca (kg/ha)
1 pre-treatment	2.8	0.03	0.84	1.85
2 post-treatment	26.5	0.26	1.98	2.60
3 post-treatment	20.5	1.12	1.97	2.53
4 post-treatment	17.3	1.27	2.41	3.17
5 post-treatment	11.9	0.25	0.88	1.66

Source: Adapted from Swank and Crossley, 1988.



Box 29.1 Figure 1 **(a, b)** Vegetation release of advance regeneration of sugar maple and beech, and recruitment after a watershed deforestation experiment at Hubbard Brook. *Source:* **(a, b)** Adapted from Anderson 1963.

reveal that the vegetation after deforestation from the most intensive silvicultural treatments (such as a true clearcut) have substantial increases in streamflow that return to normal level within 3–7 years of the impact (Fig. 29.3), and that minimal amounts of sediment and nutrients are lost. The prime reason for this is that the the regrowth of vegetation plays an absolutely critical role in usurping what nutrients would be lost, shading, which slows decomposition processes of the exposed forest floor, and incrementally reducing streamflow with increased growth, over time, of canopy coverage and transpiration (see Box 29.2 for details). However, such trends should not be generalized because more erodable soils on steeper slopes, such as sites in the Pacific Northwest, can be more susceptible to erosion from clearcutting.

Both reductions in transpiration and interception are greatest when warm weather accelerates evaporation rates. There are virtually no reductions in transpiration

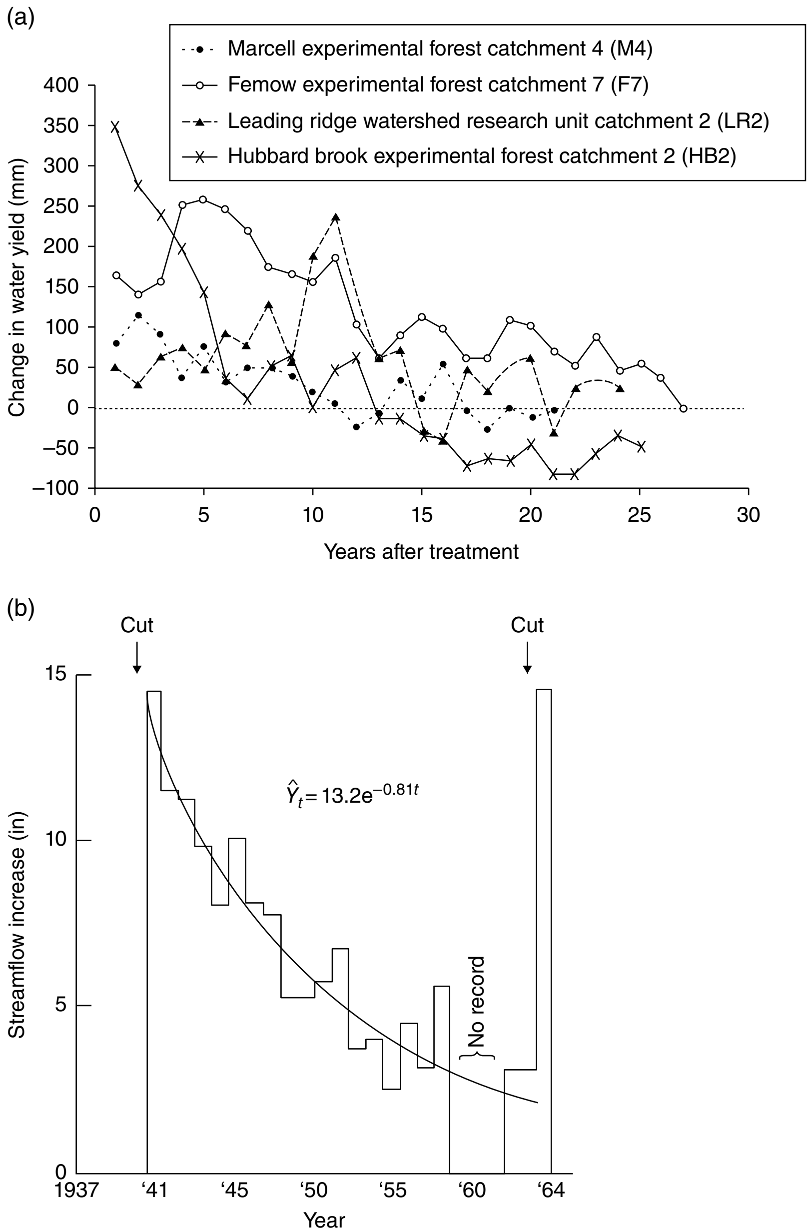


Figure 29.3 **(a)** A graph depicting water yields over years from forested watersheds that had been cut and then allowed to regrow, as compared to an adjacent control watershed that was not cut. Hubbard Brook returned to untreated conditions after 5 years, Marcell after 19 years, Leading Ridge after 15 years, and Fernow after 25 years. Differences can be attributed to climate and underlying watershed geology, but more importantly, to differences in amounts of clearance and the degree of prolonged application of herbicide. *Source:* Adapted from Hornbeck *et al*., 1996, 1997; and from Brown *et al*., 2005. **(b)** A stylized illustration of water yield increase after a clearcut over a 25-year period, as compared to an uncut watershed. *Source:* Adapted from Bormann and Likens, 2012.

when trees are leafless or are so short of water that they transpire very little. With these kinds of reductions in transpiration and interception, the higher the precipitation is, the greater the absolute amount of gain in streamflow is. Such increase of soil water seldom adds to the peak runoff associated with floods. In fact, it is ordinarily beneficial because it is most important at the very times of year when transpiration is greatest and streamflow the lowest. However, if a flood-inducing rain came soon after one of these times, the floodwaters would be increased by the comparatively small amount of water that cutting had caused to be left in detention storage.

Evergreen stands intercept and transpire substantially more water than deciduous stands. The North Carolina studies found that replacing the deciduous hardwoods with white pines caused annual reductions of streamflow of about 10 acre-inches (1030 m^3) per year for at least 10 years after the pine stands had fully closed (Swank and Crossley, 1988). These reductions extended throughout the year and were greatest during winter and spring. It may be anticipated that any cutting in evergreen forests will have a greater effect than similar cutting in deciduous forests.

The effects of tree removal are somewhat different in the case of snow, which can accumulate in wind-created drifts behind barriers or in narrow openings. Drifts provide useful ways of storing water on the land and delaying runoff in climates, such as those of the Rocky Mountains, where most snowmelt is caused by sun rather than rain.

Ordinarily, the chief effect of cutting on the water regime is to provide more water for the remaining vegetation of the site. Cutting is done for the deliberate purpose of increasing downstream water supplies only where such supplies are critical. Experiments with **maximizing** streamflow by repeated mechanical or chemical soil treatments to prevent regrowth of vegetation have been found to cause soil erosion or loss of nutrients to runoff. These effects and treatments are not those of silvicultural clearcutting, which is not aimed at denuding the landscape. Replacing forests with grasses will produce more streamflow and cause less erosion and nutrient loss, but watershed damage may result if any subsequent grazing is not stringently regulated. It should be noted that increases in streamflow may sometimes be of no advantage unless some way can be found to store water in reservoirs until it can be used.

Results from Paired Watershed Treatments: The Storage and Leaching of Nutrients

Soil nutrients and water can flow out of forests, but one objective of silvicultural practice is to restrain such losses. As is the case with natural erosion, they cannot be entirely prevented; in fact, aquatic life would suffer from the loss of chemical nutrients if it were eliminated. However, numerous studies have demonstrated the value of retaining forested riparian zones within a regenerating stand for nutrient retention of the soils, and to maintain shade, water temperature, dissolved oxygen, and bank stabilization of the water body (Brown and Binkley, 1994).

If nearly all of the vegetation is temporarily eliminated, as with true clearcutting, there is the risk that soluble substances, especially chemical nutrients, may leach out of the forest system. These inordinate leaching rates must be considered. The best defense against such loss is the continued maintenance of some sort of vegetative cover, even if the trees or other woody plants are eliminated. The next best defense is prompt reestablishment of vegetation to continue the cycling of nutrients and other soluble substances on the site.

Living vegetation is not the only buffer against nutrient loss; organic and inorganic colloidal surfaces that make up the cation-exchange capacity of the soil also play a highly important role. Soils that are high in organic matter or clays (mineral colloids) may strongly resist loss of cations such as calcium, potassium, or ammonium nitrogen, but this does not help to retain anions such as nitrate or sulfate for very long. The retention of nitrates (and the less important sulfates) depends mostly on living vegetation and conservation of soil organic matter. The question of whether phosphate anions leach away depends more on their ability to bind with iron and aluminum compounds than on anything altered by cutting practices.

Most investigations have not shown major losses of nutrients in association with natural regeneration by clearcutting. However there was a significant case involving sandy soils and the northern hardwood forests of the granitic White Mountains of New Hampshire (Bormann and Likens, 1979). In this case, the warming of the forest floor induced by clearcutting caused the quick decomposition of the thin leaves of the litter of maple, beech, and birch, and more importantly, nitrification. In this process, nitrifying bacteria convert soil ammonium compounds, which can be retained on the cation-exchange surfaces of colloids, to nitrate anions, which are free to move out in the soil solution. If late in the growing season, and the pioneer vegetation does not develop fast enough to take up the nitrates and some other highly mobile nutrients, there can be a period of some months during which accelerated losses to streamflow take place. As far as regeneration cuttings in these particular forests are concerned, the important point is to keep the cutting area widths narrow, and to place them in areas already well vegetated with advance growth. Similar losses from nitrification have not been observed in experiments in conifer forests or in deciduous forests farther south or west, primarily because the geologies are more "buffered" and are not so prone to acidification.

The retention of leaves by evergreens enhances the capacity of such species to store nutrients aboveground (Cole, 1986). The thin leaves of deciduous species usually decompose rapidly enough that they support comparatively rapid nutrient cycling, but the high mobility of the nutrients also exposes them to somewhat greater losses by leaching. Losses of nutrients in hot, moist tropical forests are so notoriously rapid that most storage of them is limited to the wood.

Managing Forests for Water Quality: Examples from the United States

Almost all forests upstream from cities on both east and west coasts of North America are surface water supplies for drinking water. Some of the largest cities have extensive forest areas that supply the cleanest unfiltered drinking water in North America (e.g., Portland ME, Boston MA, New York NY, Portland OR, Seattle WA, and San Francisco CA). All of these cities manage their forests as filters to maintain and even improve water quality that flows into reservoirs for drinking water. Gross water yield is not a major concern for the east coast because it generally receives high amounts of precipitation year round. Gross water yield on the west coast, though much higher than the interior west, has greater seasonal unpredictability than on the east coast, given a greater dependence on winter rains and build up of a significant snowpack. However, all of these cities on both coasts manage for water quality in these high-precipitation areas, but their geologies, climates, and forest histories differ.

The general silvicultural goals for managing water quality are to create a more resilient forest canopy that buffers disturbance impacts, both acute (wildfires, hurricanes) and chronic (pollutants), and also build an age-class and canopy structure that is capable of uptake and storage of pollutants and nutrients. This means a silviculture method aimed toward creating an all-aged, multi-species forest with structural complexity and vigorous growth, but shaded riparian zones. To get to this composition, age class, and structure, it would require a set of silvicultural treatments that does not remove more than 20% of the forest canopy within any one sub-watershed per decade, so as not to increase water yield. These goals and the treatments to achieve them are believed to be the best approach, based on the now voluminous number of watershed studies that have been conducted in North America.

Managing for Drinking Water Quality in the Coastal West

The west coast cities of the US receive most of their precipitation in the form of winter rain or snow, which melts and flows rapidly in the spring from steep mountain ranges. Therefore, before delivery by aqueduct to the city, water flow needs very careful regulation and storage in dammed reservoirs constructed within glacial valleys that, because of their geology, can be deep but not very wide. Reservoir storage can be fairly limited because of valley width. Much of the forest that regulates and filters the water is on steep topography on either side of the reservoir valley. A high proportion of this forest was cutover for timber in the late 20th century, before land acquisition and management as a water supply area. Some areas have succumbed to wildfires, and there is a persistent threat in regions where summers can be very dry, particularly in the west.

To move toward a more resilient forest that improves water quality for the long-term, forest managers have taken multiple approaches. Some areas have been selected for a more passive approach to promoting the vertical stratification of second-growth stands as a protective multiple-layered land cover. In other areas that have stagnated in stem exclusion, thorough release treatments have been applied. Still other areas, susceptible to potential wildfires, have received low thinnings. Steep slopes susceptible to erosion have often been left untreated. Finally, some of the more gently sloping areas have been encouraged to regenerate with patch and group selection to start creating an all-aged forest in the watershed.

Attention has also been focused on minimizing permanent road systems, particularly on slopes, and by closing many of the original logging roads and vegetating the areas by broadcast seeding, since they are the major source of sediment into streams (see section on forest operations, Chapter 23). Given the accentuated spring meltwaters, much attention is placed on using an evergreen forest canopy to promote a protracted snowmelt in spring each year. In addition, the Environmental Protection Agency and federal guidelines, as well as local regulations, ensure that water continuously flows downstream to maintain viable fish populations, especially salmon.

Managing for Drinking Water Quality in the East

Drinking-water supply areas for east coast cities have forests on much gentler sloping terrain that drain into generally larger but shallower reservoir systems that have overall longer residence times than those on the west coast. The reservoir watersheds themselves are larger than those of the west, with a land-use history of either cutover timberland or more commonly second-growth forests that have come back after a period of agricultural use. Rainfall tends to be more equitably distributed with high pollutant deposition of heavy metals and nitrates from the industrial midwest. Since much of the forest is even aged and about 100 years old, the

canopy is closed with an understory that is often limited by high shade, inhibiting regeneration and herbaceous plant establishment. The lack of forest structure and a vigorously growing understory makes this forest prone to windthrow and surface erosion. Forest watershed managers aim to create more structurally diverse age classes by use of shelterwood and selection systems that establish a vigorous understory of mixed species that rely upon advance reproduction (Box 29.2). Such a forest is capable of releasing regrowth immediately after a hurricane or tornado, and is continuously growing and sequestering nitrogen, while heavy metals are bound to a forest floor of organic matter that is itself protected by partial shade from the canopy.

Box 29.2 The Quabbin Watershed. A history of land acquisition and management of the drinking water supply for Boston, Massachusetts.

Introduction

The watershed for the city of Boston and all its surrounding towns and suburbs is dependent upon maintaining one of the cleanest and purest forested watersheds in the nation (Figs. 1, 2). Boston is in the enviable position of having an "unfiltered" drinking water system primarily because the water is filtered by nature, namely the forest. Several other cities have the good fortune to be in this same group: New York City, Seattle, San Francisco, Portland, ME, and Portland, OR. Most cities are not fortunate enough to be in control of their own watershed and therefore cannot fully control the pollutants that their citizens drink. Most cities have to invest in huge engineered filtration plants that still have only the ability to take out some of the usual suspects such as nitrates and sediments. Currently, filtration plants are now faced with a deluge of pollutants that cannot be taken out, given all the things that people flush down toilets (medicines, foods, and chemicals), or that farmers use on their agricultural fields (herbicides, insecticides, hormone growth-regulators, livestock medicines). These substances inevitably end up in the streams and rivers from which we drink. Forests and vegetation can play critical roles in protecting streams and rivers even when the whole surface watershed is not fully protected (see role of riparian vegetation in Box 29.3).

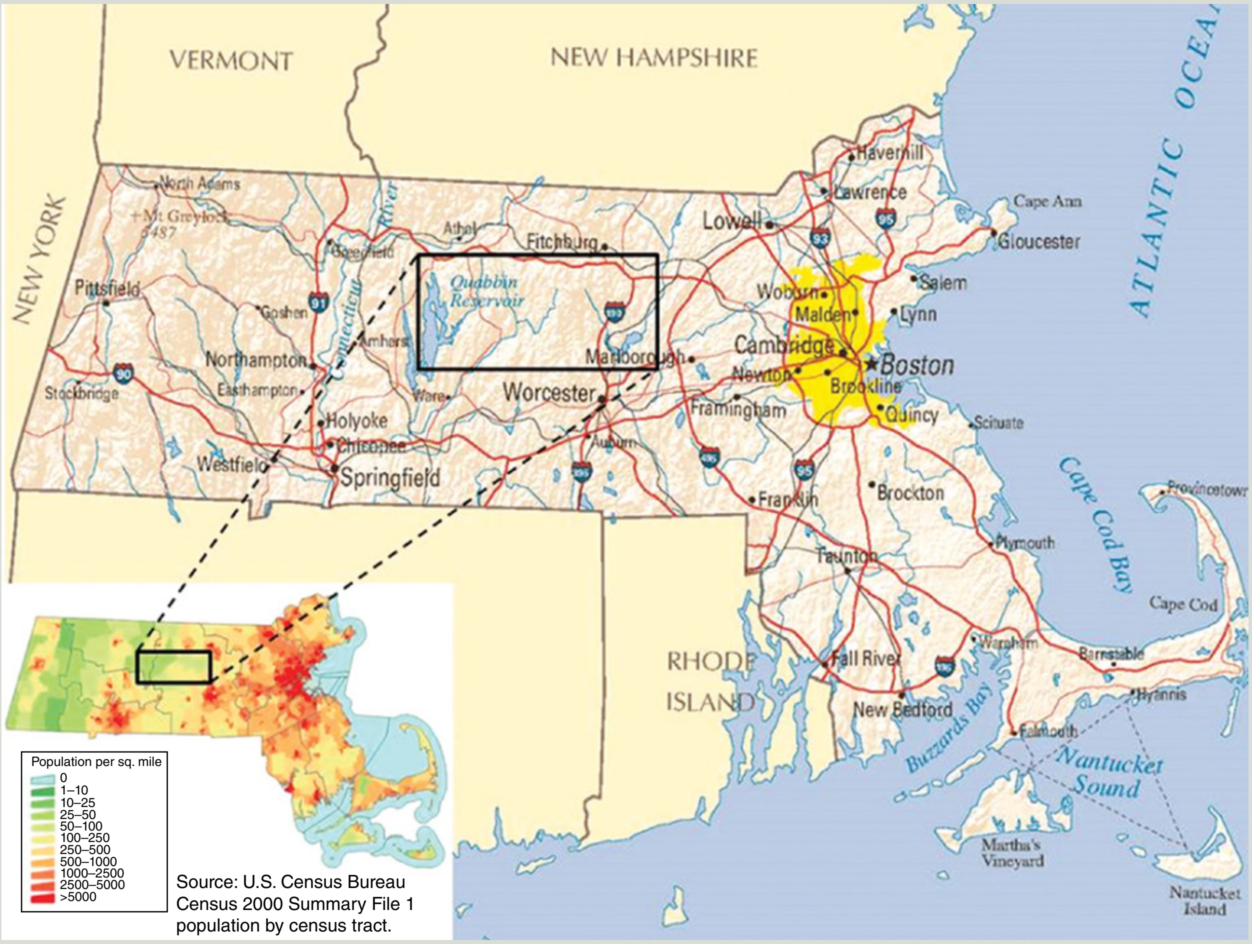
The majority of America's population obtains their drinking water from reservoirs whose watersheds are not fully protected and have significant amounts of development. In addition, many cities are dependent upon rivers, some of which are highly polluted (St. Louis, MO and

Box 29.2 Figure 1 The Quabbin Reservoir, Massachusetts. The largest drinking water reservoir in the US. *Source:* Mark S. Ashton.

(*Continued*)

Box 29.2 (Continued)

(a)



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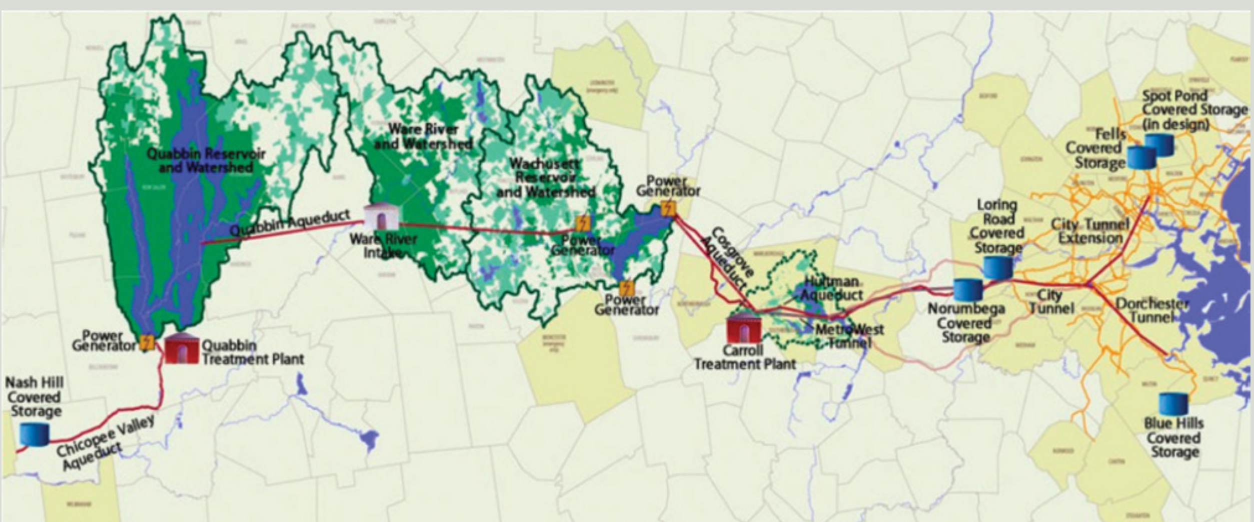


Box 29.2 Figure 2 **(a)** A map of Massachusetts showing the location of the Quabbin Reservoir in relation to Boston and its surrounding suburbs. The distance between the city and the reservoir is about 60 miles (100 km). **(b)** An illustration depicting the engineering connecting the reservoir system to its water distribution within Boston. *Source:* **(a, b)** Alcott *et al*., 2013. Reproduced with permission from Taylor & Francis.

Box 29.2 (Continued)

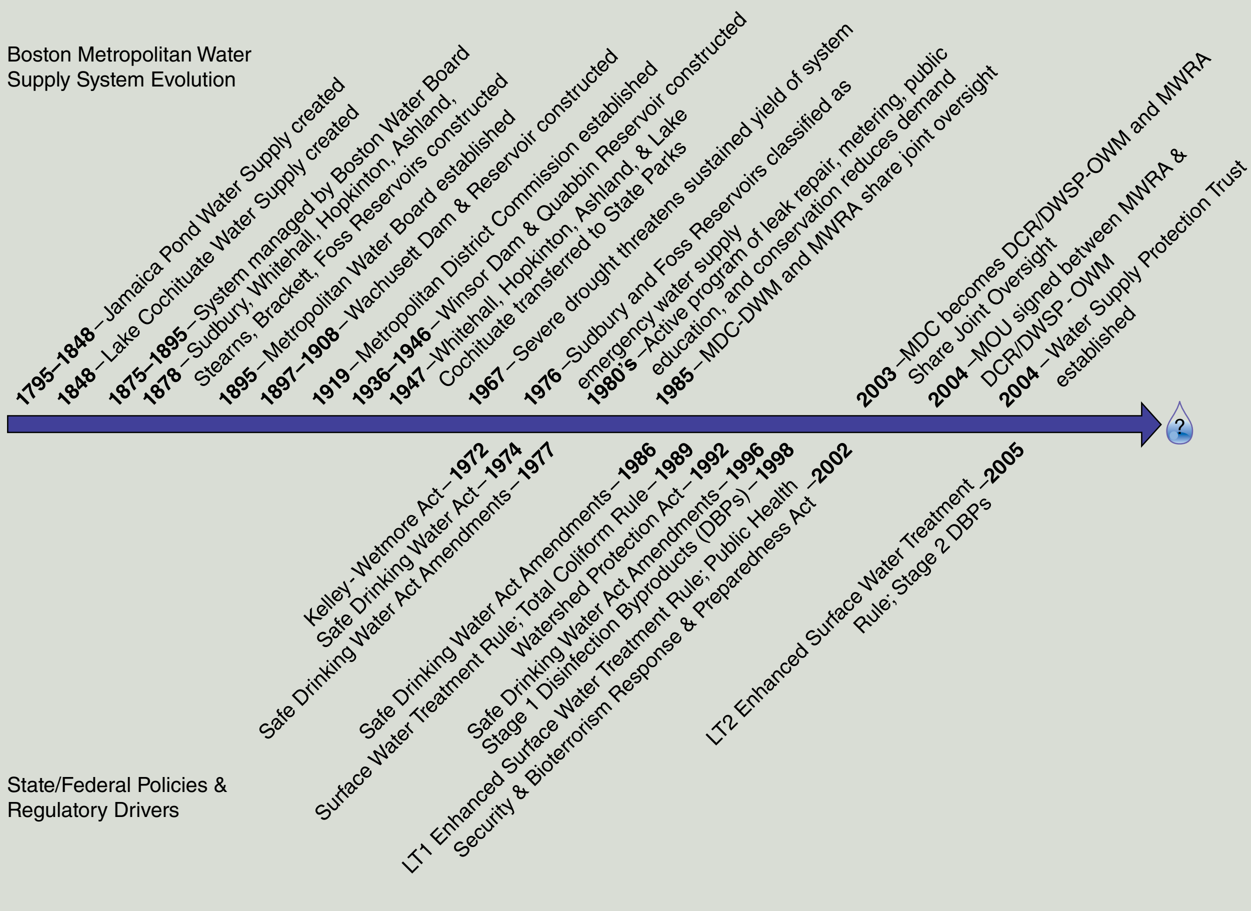
New Orleans, LA both depend upon the Mississippi River). Still others in the west are mining the groundwater supply (Phoenix, AZ).

The Quabbin

The Quabbin Reservoir was built in the 1930s and was hoped to be a final answer to Boston's continuous demand for drinking water. At the time, the supply watershed extended further and further west, and was failing to protect the quality of the drinking water (Fig. 3). When the Quabbin was built, the land was acquired by eminent domain and was extremely controversial. It has served the city well, with over 90,000 acres (36,000 ha) owned and managed by the Massachusetts Water Resources Authority (MWRA) out of the 117,000 acres (48,000 ha) that make up the watershed (Table 1). About 75% of the total acreage within all of Boston's drinking supply watersheds are now either directly owned or protected by easement as forest.

Managing the Forest Watershed

The Massachusetts Water Resources Authority (MWRA) manages the forestland around the Quabbin Reservoir and Ware River with the purpose of increasing the structural and species diversity of the forest to act as a more resilient long-term filter. The history of the forest is one of past agriculture that was followed by old-field pine. It was subsequently cut for packaging in the early 1900s or blew down in the hurricane of 1938. The existing hardwood forest is mostly 75–100 years old, having been released beneath the pine after these events. The silviculture practiced is intended to create a vigorous groundstory in order to respond immediately to any future wind events, with a diversity of species that provides less susceptibility to invasives, insects, and disease. The management protocol is to convert the even-aged, second-growth forest into multiple-age stands with irregular shelterwoods that encourage vigorous establishment of the widest array of species and regeneration mechanisms (shade-tolerants and -intolerants, advance regeneration,



Box 29.2 Figure 3 A timeline of major development and policy events related to Boston's drinking water supply. *Source:* Alcott *et al.*, 2013. Reproduced with permission from Taylor & Francis.

(*Continued*)

Box 29.2 (Continued)

sprout growth and seed origin) (Science and Technology Advisory Committee Report, 2012) (Fig. 4). The opening sizes are regulated to no more than 0.5 acres (0.2 ha) to ensure continuous canopy cover, but they are uniformly applied across the whole stand to encourage relatively uniform vigorous regeneration establishment. Riparian zones are treated differently in that individual trees within 50 ft (15 m) of a waterway are taken in what can most appropriately be labeled as a variable-retention thinning. This is to both encourage different size classes and structures along the waterways and provide for a continuous uniform canopy cover for shade. All of this is to promote a forest that is actively sequestering pollutants and is poised to respond to the next unpredictable disturbance event or an insect or disease occurrence (Science and Technology Advisory Committee Report, 2012).

Box 29.2 Table 1 A summary of the watershed areas, their average yields (in millions of gallons per day), and the average withdrawal.

Source	Watershed area[1]		Average annual outflow[2] (million gall/d)	Average annual withdrawal (million gall/d)
	Square miles	Acres		
Ware River (MWRA intake)	96	61,740	110.0	8.08[3]
Quabbin Reservoir	187	119,940	195.2	137.9
Wachusett Reservoir	117	74,890	127.4	123.1
Total DCR/MWRA water supply system	401	25,6570	432.6	261.0

Source: Alcott *et al.*, 2013. Reproduced with permission from Taylor & Francis.
Source: Watershed statistics – DCR/DWSP/OWM GIS; Water withdrawal statistics – MWRA, 2003
[1] Including area of reservoir surface for Quabbin Reservoir and Wachusett Reservoir
[2] Outflow includes withdrawals and downstream releases
[3] This is not a supply but a transfer to Quabbin Reservoir

(a) (b)

Box 29.2 Figure 4 Examples of the irregular two- to three-aged (multiple-aged) shelterwoods being used to encourage a vigorous understory with a diversity of species and size classes in the canopy. **(a)** Mixed hardwood on glacial till soils. **(b)** Pine on outwash soils. *Source:* **(a, b)** Mark S. Ashton.

(a)

Managing Forests for Water Quality in Agricultural Landscapes

Agricultural landscapes are major sources of non-point source pollution, mainly from use of both inorganic and organic fertilizers on tilled croplands (Allan, 2004). Riparian zones link streams with terrestrial croplands and are therefore the most important zone of management before pollutants enter a stream. In small to medium streams, forested riparian zones moderate water temperatures, reduce sediments, provide organic matter mostly as leaf litter as a food source of aquatic organisms, and provide structural stabilization to stream banks. Forested riparian zones can take up 90% of the nitrate and phosphorus pollution in shallow groundwater seepage into the stream (Peterjohn and Correll, 1984; Lowrance *et al.*, 1984; Osborne and Kovacic, 1993). However, during winter when trees are dormant, some of the sequestered phosphorus is released (Osborne and Kovacic, 1993). When riparian zones are more actively managed by coppice systems on short rotation, the much greater long-term potential of nutrient uptake can be accomplished with repeated harvests (Fig. 29.4).

(b)

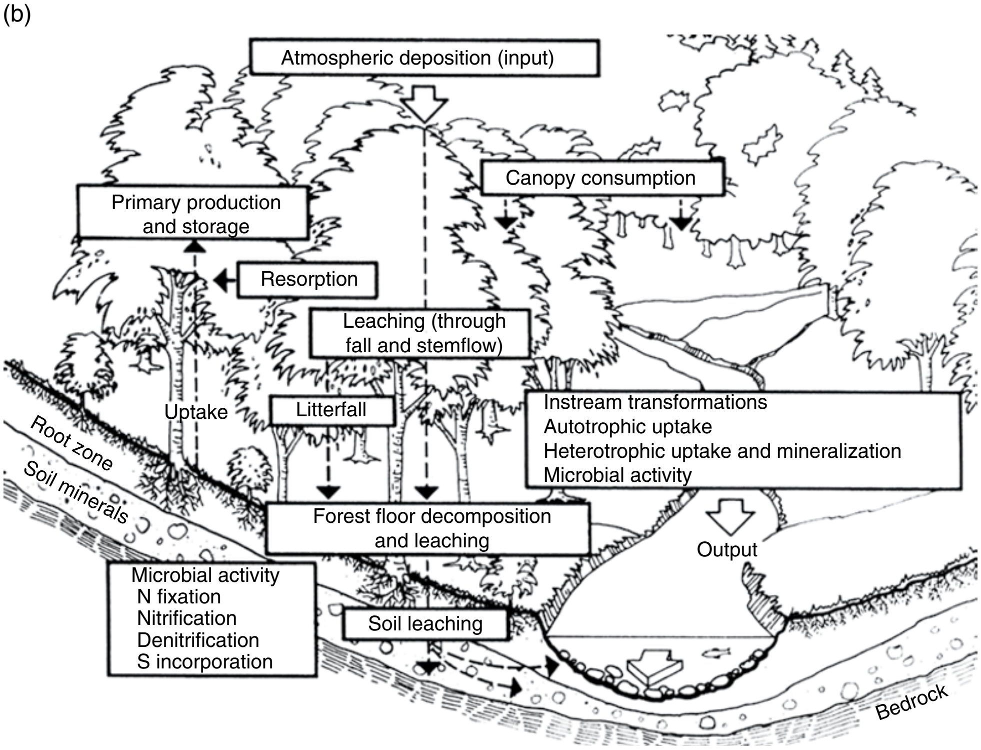


Figure 29.4 Depictions of management zones to maximize nutrient uptake and minimize loss. **(a)** An aerial image of an agricultural landscape. *Source:* USDA Natural Resources Conservation Service. **(b)** An illustrated forested riparian zone. *Source:* Adapted from Bormann and Likens, 2012.

Managing Forests for Water Yield: Examples from the United States

Managing for Drinking Water Quantity in the Inland West

Forested watersheds managed for water quantity are usually in regions where precipitation is low and strongly seasonal, and occurs mostly as snow. Snowpacks then relinquish meltwaters downstream in spring. Such surface mountain watersheds drain into reservoir systems that supply drinking water and agricultural irrigation in the large valleys below. The best examples of this are within the intermountain west for such cities as Denver CO, Santa Fe NM, and Salt Lake City UT. Although the major concern is increasing water yield, it must not be to the detriment of quality. Forests in the region were subjected to heavy cutting and grazing at the end of the 20th century. With wildfire suppression and their even-aged, second-growth origin, forests are now overstocked and very susceptible to catastrophic wildfires, insect outbreaks, and disease. Goals to make the watershed more resilient include a dramatic reduction in stocking and a reintroduction of an all-aged forest with greater structural diversity, vigor, and capacity to store water as snow for longer periods on site for a more delayed release in spring.

Silvicultural treatments to achieve these goals would be to complete heavy low thinnings (restoration thinnings) in many overstocked stands that can then reintroduce groundstory burns to maintain open park-like stands (Box 29.3). Water will become more freely available, creating more vigorously growing trees. Regeneration methods that follow the contours of slopes in order to diversify age class and structure, such as strip-shelterwood and selection systems, can be used to increase snowbanks on slopes, and act as temporary firebreaks before regeneration of a new stand is established (Fig. 29.5).

Box 29.3 The forest management of the municipal watershed for Santa Fe, New Mexico.

Introduction

Like many cities in the intermountain west, Santa Fe is dependent upon a surface drinking water supply area that is forested and in the uplands and mountains nearby. The Santa Fe municipal watershed, including about 17,000 acres (7000 ha) of Santa Fe National Forest, supplies 30,000 households from two catchment reservoirs. A fund for ecosystem services has been created for protecting the watershed with the aim of restoring the forest to a structure and age-class distribution that makes it more fire resilient. The payment amounts generate about $200,000 per year to maintain the watershed after restoration. The money is generated by a small fee on the water user based on consumption.

This plan was triggered by catastrophic wildfires that have created huge sediment loads and erosion, concerns both in this region and elsewhere. For example, both the Buffalo Creek Fire (1996) and the Hayman Fire (2004) in Colorado produced sediment loads that filled the reservoir systems belonging to the city of Denver. Had the authorities been more proactive and treated the forests surrounding the reservoirs to open the forests up, removing much of the undergrowth, an enormous expense would have been saved in clearing out and remediating the reservoirs.

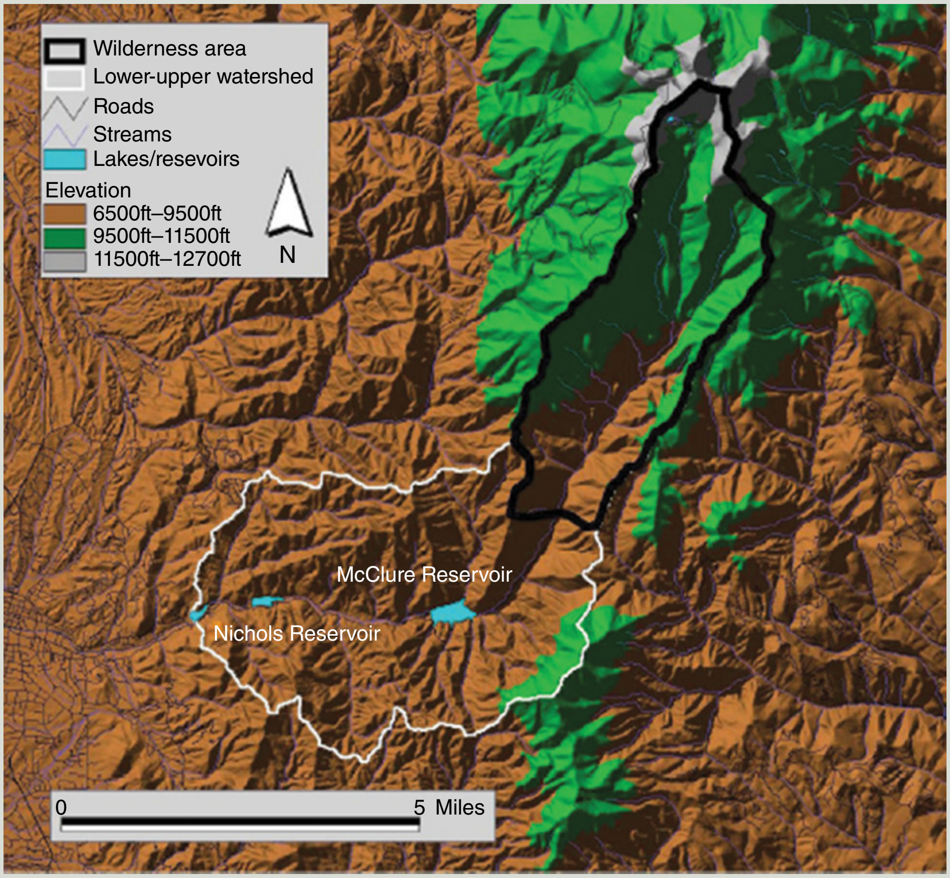
Forest Management

The watershed can be divided into three management zones (Fig. 1). The lower watershed land is around the reservoirs, amounting to about 7000 acres (2800 ha), and varies in elevation range between 6500 and 9500 ft (2000–3000 m). It is dominated by the mixed conifer type. This includes ponderosa pine, pinyon pine/juniper woodland, and Gambel oak. This area has had a restoration treatment, taking much of the small-diameter growth of vegetation that has come in over the 100-year period of fire suppression. The restoration treatment encompassed a mix of low thinnings and variable-density thinnings that opened up the understory. The cut material was either chipped or burned in piles. It is intended that about 1000 acres (400 ha) of the area will be broadcast-burned each year on a 7-year cycle. Areas and individuals of southwestern white pine, a relatively rare tree, will be protected from the burns. At the same time, invasive encroachment and spread will be monitored and controlled, especially in the case of cheatgrass. Maintaining open forest stands and preventing ingrowth minimizes the risk of crown fire and catastrophic loss of forest cover, thus minimizing potential sheet and gully surface soil erosion into riparian zones. Transpiration loss from trees is reduced and snow interception and spring melt increased to increase total water yields downstream, making the watershed more resilient to drought.

The second management zone includes all waterways and associated riparian zones. This involves careful monitoring of the functional integrity of all waterways, and protecting the vegetation within the buffer zones around the water. Maximizing the vegetation cover around the waterways shades and cools the water, reduces nutrient leaching, and minimizes sediment loss and erosion into the water. Any invasive encroachment is controlled.

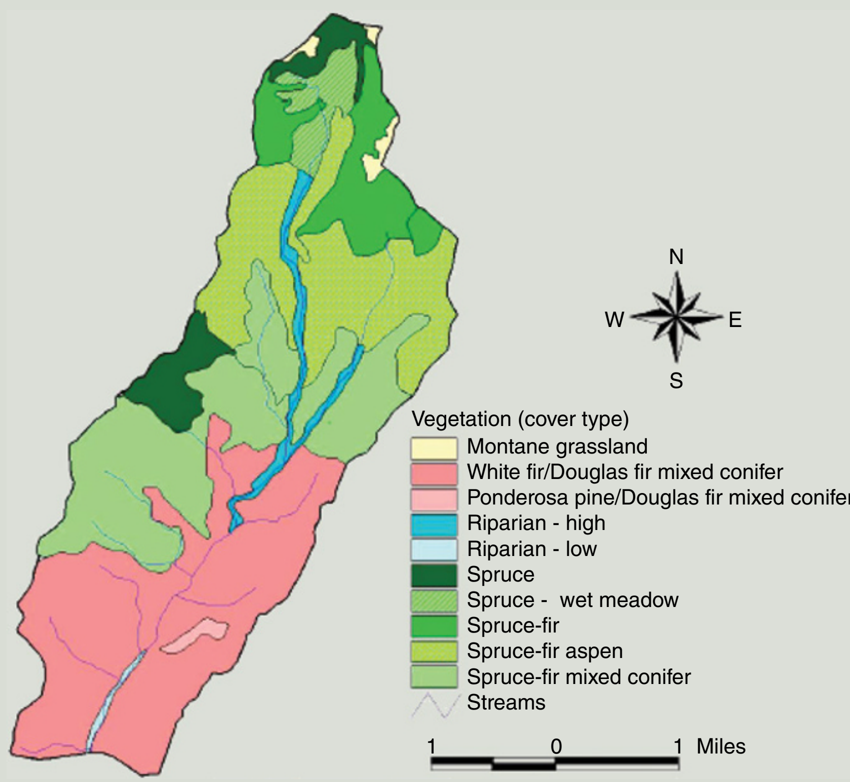
The third management zone is the remaining acreage of land that is at high elevation, consisting of more than 9500 acres (3800 ha). Most of this is in the Pecos Wilderness Area of the national forest and is composed of white fir/Douglas-fir at the lower elevation, and spruce–fir and alpine meadows at the higher peaks (Fig. 2). There is no management other than monitoring for signs of forest health decline and invasive encroachment.

Box 29.3 (Continued)



Box 29.3 Figure 1 The Santa Fe municipal watershed encompassing about 17,000 acres (7000 ha) of Santa Fe National Forest. The black line depicts the upper watershed and the Pecos Wilderness Area. The white line depicts the lower watershed. *Source:* Margolis *et al.*, 2009. Reproduced with permission from E. Margolis.

Box 29.3 Figure 2 The vegetation zones of the Pecos Wilderness Area. *Source:* Margolis *et al.*, 2009. Reproduced with permission from E. Margolis.



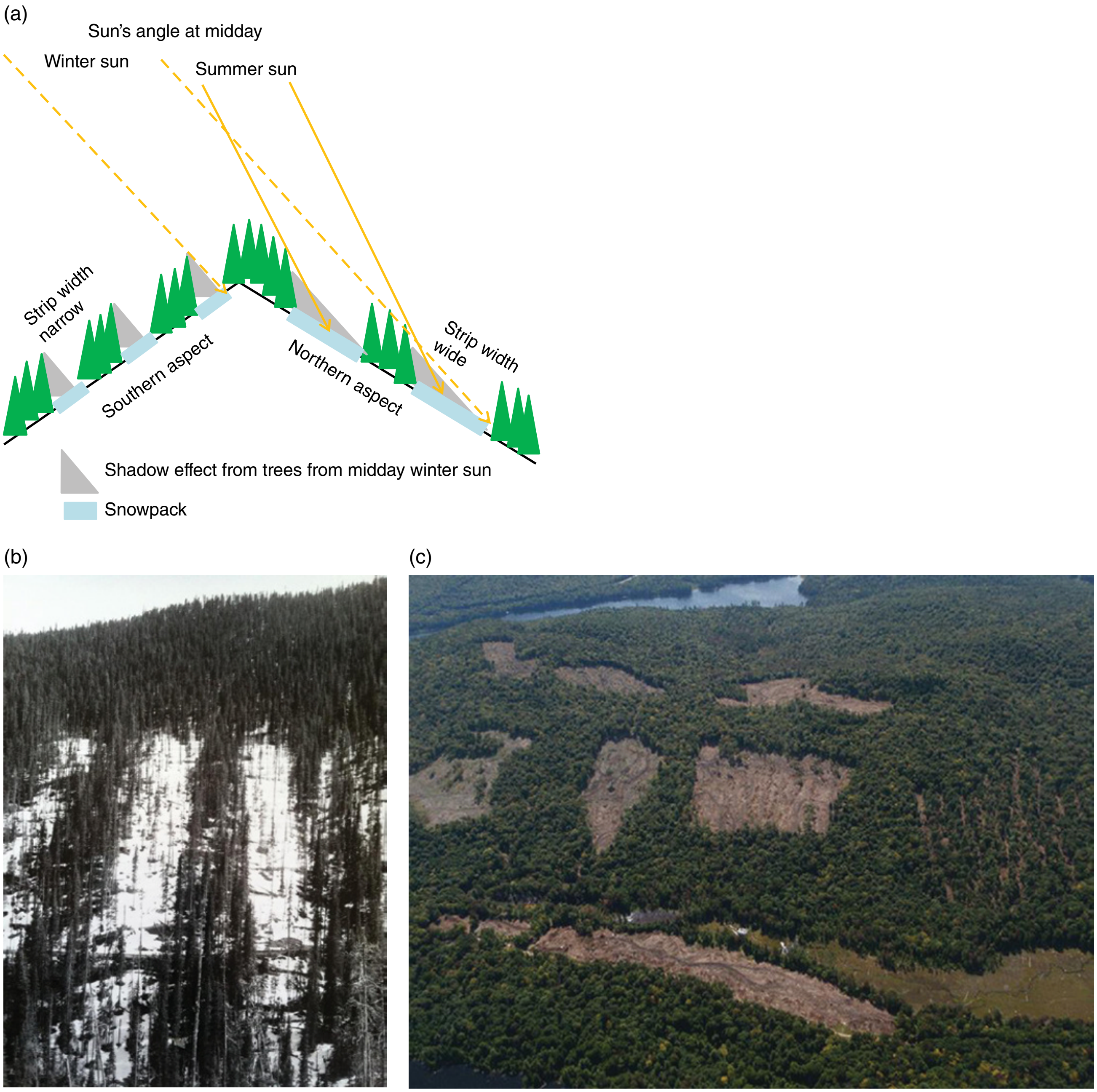


Figure 29.5 Regeneration methods to increase snow bank storage on southern and northern aspects of mountain slopes. **(a)** Steep topography encourages a "wall-and-step" process of increasing snow accumulation in the shade of openings that parallel the slope as strip cuts. These can be made permanent and converted into meadows, or incorporated into natural regeneration methods that progress up-slope or down-slope with strip shelterwood, strip clearcut, or strip selection systems, depending upon the autecology of the forest type being regenerated. The width of the strip depends upon the aspect and seed-dispersal abilities. *Source:* Adapted from Anderson, 1963. **(b)** A photograph of the "wall-and-step" strip-shelterwood of Engelmann spruce–subalpine fir in the front range of Colorado. *Source:* US Forest Service. **(c)** On flatter topography, such as in the photograph of the Adirondacks, patch cuts can serve as a way of increasing snow accumulation and increasing subsurface annual water yields. *Source:* Protect the Adirondacks. Reproduced with permission from Protect the Adirondacks.

Forests as Novel Water-Yield Catchments

Fog-drip is a kind of precipitation that is reduced or prevented by clearcutting or by deforestation. It forms when the tiny suspended water droplets of clouds are blown through leaf canopies, swept out of the air, and coalesced into droplets large enough to fall to the ground. This kind of precipitation by interception can be very significant in some "cloud forests" at high

elevations, and in some of the remarkable kinds of forests that occur along the foggy western shores of continents at middle latitudes. The coast redwood and western hemlock–Sitka spruce forests of the western edge of North America are heavily watered from this source, as are the high-elevation forests of the tropics and subtropics. The degree to which heavy cutting harms such forests is not known, partly because of the difficulty of measuring fog-drip precipitation accurately. Conventional rain gauges that are exposed beneath the open sky do not collect fog-drip. It is likely that the most serious harm is to germination and establishment of seedlings starting in the open (Asbjornsen, Ashton, and Vogt, 2004). The most important forests that act to capture water because of their vertical structure and stratification are very restricted in geography, but can be very important sources of water for downstream agricultural systems.

This kind of precipitation can also cause damage. When supercooled cloud droplets impinge on solid objects and freeze, they form a white ice called **rime**. Because of their large surface area, these droplets also absorb large amounts of sulfur dioxide and other atmospheric pollutants. These are the cause of much of the past damage from acid "rain" in forests of the northeast mountains (the Adirondacks, White Mountains, and Green Mountains) that are frequently enshrouded in fog or cloud.

Summary

There is no better means of conserving the renewability and productivity of terrestrial ecosystems than keeping the growing space full of vigorous forest vegetation. As long as the vegetation continues to accumulate biomass, it is in what has been called the aggrading phase of its development. This means that it is not only adding to the standing crop of biomass, but also accumulating nutrients, trapping pollutants, sequestering carbon on the site, and filtering and regulating the flow of water.

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30

Industrial Timber Management

Introduction

As the world's population continues to grow, the demand for wood products has also increased. The total world's forestland that is used for the growing of wood products continues to decline because of land-use conversion to cities and towns and their infrastructure, agriculture, and mining and oil exploration (Lindquist *et al*., 2012). With increased globalization, wood products are now traded throughout the world, linking the demands and the supplies of countries. New engineered wood products continue to be developed, changing the demand for different species and stem characteristics. Current industrial forestlands, particularly from the private sector, contribute disproportionately more timber and wood products than other forests that are publicly owned.

This chapter is organized such that the first part covers the management principles of regulating a forest chiefly for timber using methods that use timber area and standing volumes. Comparisons are made between economic and biological mechanisms for determining rotations. The second part covers the regional trends in industrial forestry both within the US and the world more generally.

Principles of Regulating Timber Harvests

The history of silviculture and forest management has been described in Chapter 1; however, for the last century, silviculture for wood production was such an overriding consideration, that forest management in North America was focused almost solely on timber as the objective. Other considerations, such as wildlife habitat and water quality, were considered to be constraints on timber management. This was especially the case from the 1940s to the 1980s. Many forestry programs followed this trend in their curricula. Mathematical techniques, such as linear programming, institutionalized this single-purpose perception. These mathematical optimization equations used a single "objective function," and managers strove to maximize the economic value of the forest, which was soon described as a net present value (NPV) of the forest (described later in this chapter). Maximizing the timber value of the forest became an exercise in scheduling harvests (income), and stand-regeneration methods and tending operations (costs), in a way that optimized the cash flow discounted to the present. Concerns about wildlife and aesthetics were reduced to numerical constraints on NPV, such as restrictions on the size and location of cutting areas and the minimum age of trees at time of harvesting. Current social conditions have changed and even the most intensive sustainable forest management necessitates the consideration of multiple goals and, as a result, simple linear programming can lead to an undesired outcome.

Although the fundamental objective of silviculture is better thought of as tending forest stands in a way to produce stand structures over the course of time that can be used to provide a variety of goods and services, the production of wood products will generally remain the dominant, if not sole, hard currency income source in many circumstances. Cutting is the chief tool by which the forest is controlled; this is true even when the main objectives are the management of resources other than timber, such as water, forage, wildlife, or recreation. The cutting and removal of trees is the most costly forest operation. In most instances, the objective of cutting is to proceed so that the value of the products substantially exceeds the cost of harvesting and subsequent operations. However, the opportunity to recoup even some of the removal costs by conversion to wood products can make it possible to grow forests for aesthetic or other reasons at an endurable expense. Therefore, no matter what the overall objectives of the landowner, timber management in almost all cases will remain in the forefront of the silviculturist's concerns.

If timber management is the landowner's primary objective, the regeneration system that is used must be matched not only with the species and site, but also with the rotation length, product markets, and rate of stand development. Often it is assumed that

The Practice of Silviculture: Applied Forest Ecology, Tenth Edition. Mark S. Ashton and Matthew J. Kelty.

managing for timber means clearcuts and monoculture plantations. Monocultures are often used, not for biological efficiency, but because of real or perceived market constraints. Industrial forest landowners often own land to meet the needs of specific mills. In that case, it can be advantageous and more profitable to produce a crop with very uniform stem or fiber characteristics. This is why most industrial forest landowners in the southeastern US grow loblolly pine or slash pine which have those characteristics. Monocultures of any species are not only unnatural but difficult to maintain. Single-aged monocultures usually provide the most financial benefit for the single purpose for which they were designed, but they have the least financial flexibility as markets change over time.

Considerations for Timber Production in Forests

Wood Utilization

The value of a tree is based on the combination of the products that can be created from that tree and the cost of shipping the wood to a manufacturing facility. Wood can be thought of as falling into three categories. The first category is solid wood products. These are from wood of various sizes sawn from a log. A second category is engineered wood products, where pieces of solid wood are glued together to form a product that may be larger, stronger, or more uniform than solid pieces of wood that can be sawn from a particular log. The third category consists of products where the fibers and chemicals in the wood are completely dissolved, which includes pulp for paper and chemicals such as ethanol for bioenergy, and other chemicals that are used for formulations such as rayon.

Solid wood products are of two types. One type is used for construction, and the value of that piece of wood is a function of size, defects such as knots, and species. Knot-free conifer logs that are straight and also have straight grain are the most valuable. In the past, large-diameter trees garnered a premium because both small and large pieces of lumber could be sawn. However, engineered wood products have taken over the market for large pieces of lumber, and there is little premium for growing large-diameter conifer trees. The other type of solid wood product is used for furniture and wood trim that are valued, based on visual characteristics. Generally, hardwood species are used for these products. During the machining, short pieces of wood are used so that defects in a log can be cut out and discarded.

Engineered wood products are pieces of wood that are glued together to increase length or thickness. Construction lumber can be used as short pieces that are glued end-to-end in a process called finger jointing. Lumber can also be glued surface-to-surface making laminated beams the thickness of many individual pieces of lumber. Wood can also be shredded and glued together either in flat panels such as oriented-strand board or in thick pieces such as Paralam™. The oldest engineered wood product is plywood, where sheets of wood are sliced from a log using a lathe, and then layers of the thin sheets are glued in orthogonal directions. The main advantages of engineered wood products over solid wood products are greater dimensional stability because of controlled fiber direction, increased piece size eliminating the necessity for large logs, and greater strength uniformity.

Dissolving wood in order to obtain **wood fiber products** such as pulp, is mainly done to produce paper. Paper products have added value if the fiber length is uniform. Dissolving wood in order to obtain basic chemical constituents such as ethanol has little dependency on any wood attributes that can be affected by silvicultural practices. Also, firewood can be used for heating in either the standard method of burning, or with the use of wood pellets and newer gasification methods.

Rotation Length

Within the general concept of sustainable forest management, timber management includes an expectation of sustained yield. Managing for a sustained yield of timber does not necessitate maximizing the yield. Often, there is some degree of confusion about what type of yield is being sustained. It is often enforced using a simple concept of board-feet, cubic feet, or cubic meters. This oversimplification negates the fact that not every cubic foot is as desirable as every other cubic foot. Some stems have higher value than others because of differences in characteristics such as species, size, form, or defects. Critics of sustained-yield management point out that this concept implies an oversupply of timber when supply is adequate and prices are low, and an undersupply of timber when supply is lacking and prices are high.

If the forest is being managed using even-aged stands, the yield of wood is estimated by using the concept of rotation, which is a repeated harvest and regeneration of stands when they reach a certain age. In 1849, the German forester Martin Faustmann laid out the calculations needed to deal with rotation length, amount, price, and discount rate of timber to produce the desired outcome. These ideas are still a part of current forest-management methods, called the Faustmann formula, with a multitude of additions and modifications (Buongiomo, 2001).

With uneven-aged management using a balanced age-class distribution, a cutting cycle is used; partial cuts of mature stands are made at relatively short intervals with continual regeneration within the stands. Either way,

there is the underlying principle that a certain (and consistent) amount of wood is harvested periodically. Thus, when using even-aged management rotation length, it is a measure of how old the trees will be at time of harvest.

Maintaining a sustained total cubic yield is carried out by determining a **physical rotation** length (sometimes called a biological rotation length), where stands are cut at the time of culmination of mean annual increment. As simple as this concept seems, it can be precisely applied only if good annual yield predictions are available from either an empirical yield table or a growth model. Incorporating losses from insects, disease, storms, and fires compounds the difficulties of applying this concept. Setting this type of rotation length is especially difficult in mixed-species stands (Fig. 30.1).

Alternatively, a **financial rotation** can be determined. This method has the goal of optimizing monetary return on capital under the soil rent principle (Bettinger *et al*., 2009). The optimal financial rotation is reached when the highest net present value (NPV) is achieved, discounting all costs and all revenues back to the same starting time. If a high interest rate is chosen for this discounting, the rotation length will be quite short. If the chosen interest rate is zero, then the financial rotation and physical rotation are equal.

Another type of financial analysis is called financial maturity. This considers the interest rate that growing trees earn on their own value. The realizable value of the stand at any point in its development is treated as an investment, and the rotation is ended when the increasing value of the stand ceases to exceed some desired rate of compound interest. In other words, if the desired rate of return is 5%, then the stand will be harvested when the annual growth rate in monetary value goes below 5%. The return on this kind of investment is zero until the first day one tree in the stand is suddenly worth one penny of net value. On that day, the compound interest earned with that one penny, on an investment of zero the day before, is infinitely high. From that date onward, except for the important effect of trees improving in value because of a quality improvement or becoming suitable for products of higher value, the rate of compound interest earned on this investment represented by the stand steadily decreases. However, this rate of decline can be slowed or temporarily reversed by commercial thinning or any other activity which increases the value of individual stems.

Other Financial Factors

Sometimes special circumstances dictate special financial needs. Forests often can provide short-term relief because of the unusual flexibility of the investment. One case is cash-flow constraints. Some owners, particularly small landowners, may need cash, even though their forest may not be financially mature. Lending sources have been reluctant to accept growing timber as secure collateral for loans because of the perceived risk in timber management. Some owners have a strong aversion to assuming debt at any cost. The owner may harvest to obtain the needed cash, even though the harvested stands may not have reached either an optimal physical or financial rotation. Another example of cash-flow constraints for small landowners is the need to meet annual cost, such as property taxes. These owners may have the need to harvest every year to pay these bills.

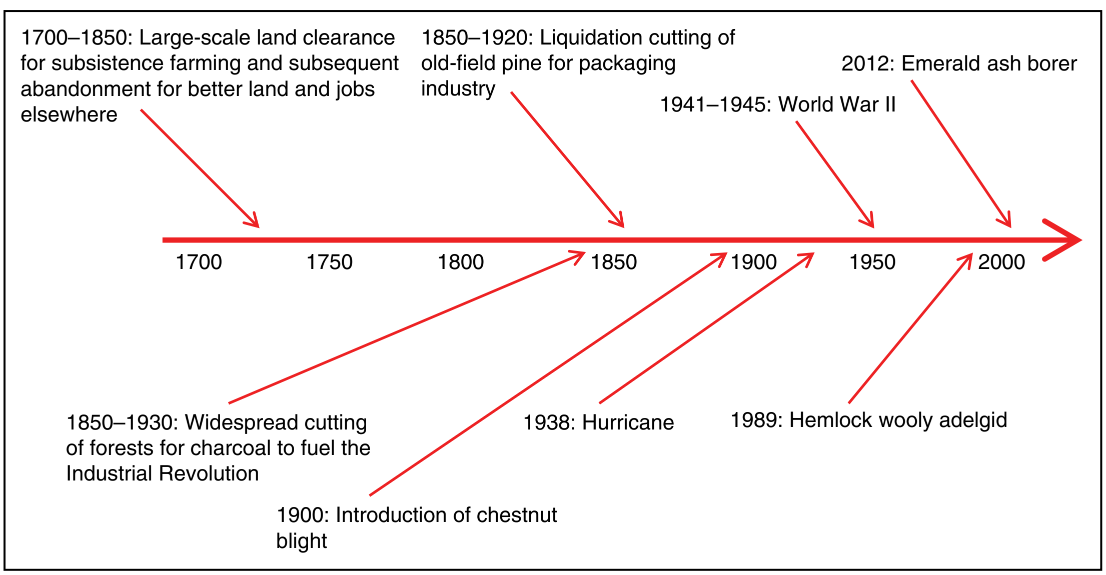

Figure 30.1 The history of disturbances in New England hardwood forests over the past two hundred years making the construction of empirical yield tables impossible. *Source:* Mark S. Ashton.

Large landowners may also have cash-flow constraints. A typical problem is a large debt to service after a major acquisition such as land or mills. The company may choose to liquidate growing-stock timber on forest stands, in order to reduce debt and increase dividends and stock prices, even though this jeopardizes future yields. The opposite condition sometimes develops when a company builds up certain age classes to solidify timber self-sufficiency for their mills, which can improve their bond rating and reduce their future borrowing costs.

Analysis of Stand Increment

No matter what system is being used to determine rotation length and the scheduling of other timber harvest operations, it is imperative to understand the concept of stand growth rates. The bookkeeping needed to track the change in the amount of wood in stands and forests can be complex. In the first place, there is the problem that the change or "growth" is usually determined from measurements that are made at two different times. Each measurement itself is subject to errors, so this "growth" (the difference between two measurements with high variance) is an estimate with even higher variance.

Second, it is important to subdivide the "growth" into its components. The trees that are present at both the beginning and the end of the period are called "survivor growth." Other components include the volume harvested during the period, and the mortality that took place but went unsalvaged. The growth of the trees that took place during the period but died before the second measurement cannot be determined by repeated plot measurements. It may be noted that the growth loss from unsalvaged mortality counts very heavily against the survivor growth of that period. This is because the loss is not merely of what grew during the period but also the loss of all production that had previously accumulated in those trees.

This is counteracted in some degree by another important artifact of the bookkeeping, which is "ingrowth." Ingrowth takes place when trees pass some arbitrary minimum diameter at breast height (DBH) and are counted for the first time. This contribution to production is magnified because these trees suddenly acquire a substantial volume, much of which was really laid down before the measurement period started.

In a perfectly balanced uneven-aged stand (or forest), these components would theoretically be the same in each successive period. Because most stands and forests are unbalanced, the magnitude of these components fluctuates markedly from one measurement period to another. However, by keeping track of the separate components, it is possible to more dependably analyze the growth of forests, and reduce the risk of large errors in the production. There is even more opportunity for error if volume estimates are made in board-feet rather than cubic volume. The ingrowth, a component always difficult to assess properly, is usually very large when measured in board-feet. The board-foot volume of a tree increases so rapidly with diameter that small fluctuations in the diameter distribution can cause remarkable differences in the apparent growth. This phenomenon is accentuated by the use of misleading log rules. For example, the Doyle Rule overestimates volume in diameter classes that are less than 22 in (56 cm).

The choice of mensuration units is important in any calculation of stand growth. If wood is to be chipped for bulk products, such as pulp or particle board, or if it is used for fuel, the appropriate units would be merchantable volume or dry tons, ordinarily with small diameter limits. With this kind of utilization, rotations would be short and any advantages of thinning small stems would be lost. If the trees are to be made into sawn or sliced wood products, the units are more likely to be board-feet in the United States or cubic meters elsewhere, each with comparatively large diameter limits set on how much wood is counted. With this approach, the rotations are comparatively long and the effects of thinning on diameter growth become crucial and controlling.

None of these approaches really solve the problem of taking the economic effect of tree diameter fully into account, because all include the simplistic assumption that all units of any given kind of product are equally valuable. Studies of logging costs and product values would have to be used to determine the true net value of units (such as cubic feet) of products from trees of differing size (and, for that matter, quality). If this line of logic is followed to the end, the most logical physical rotation would be that which maximized mean annual increment of money, which is a better measure of social utility than cubic volume. Financial rotations would be determined by the same calculations except that their length would be shortened by taking the time value of money into account.

Regardless of which economic or financial methodology or mixture is followed, there is the greater fact that the simpler the measured assumptions about mensuration units and net value, the shorter will be the rotations compared with those that would prevail in a state of full knowledge. The only assumption that logically shortens rotations is the selection of a higher rate of compound interest under soil rent, and the logic of this depends on whether the chosen rate is appropriate to the circumstances. One pragmatic way of dealing with this general situation might be to calculate a rotation from simplistic assumptions and then lengthen it on the basis of intuitive judgment about those less knowable factors that tend to lengthen rotations.

Harvest Regulation

There are two primary ways to plan an annual harvest to achieve a sustained flow of wood off the land. One is

called the **area method of regulation** of the cut. This consists of dividing the total forest area into as many equally productive units as there are years in the planned rotation and harvesting one unit each year. Such management works very well under the coppice system, because there is no kind of reproduction more certain or prompt than that which comes from stump sprouts. It was almost equally successful in growing conifers by clearcutting and planting, a system that imitated agriculture and represented the next step toward more efficient timber management. With such a scheme, reproduction was also reasonably sure and could be obtained without delay.

If a sustained yield of timber were the only objective, or if the coppice system and the clearcutting and planting were the only silvicultural systems, there would be no need of any other method of regulating the cut. This kind of forestry with fixed rotations and annual cutting areas does not provide for management with many objectives or with non-uniform stands. However, it is still often used in areas devoted to industrial forestry with the aim to satisfy the needs of certain mills. In these situations, area regulation can be applied without great difficulty if the stands are essentially even aged, and partial cutting is limited to measures such as thinning and simple types of uniform shelterwood cutting. However, this method becomes very difficult to apply when individual age-class units are too small for practical area measurement or in most kinds of uneven-aged stand conditions.

Alternatively, the **volume method of regulation** of the cut is used to determine the allowable annual or periodic harvest in terms of volume of wood, considering the rate of growth, both current and potential, and the volume of growing stock, both existing and desired. This means that if it is possible to determine and create the appropriate volume of growing stock made up of the proper distribution of sizes and kinds of trees, it could be possible to depend on having a certain well-defined volume of wood available for harvest. If this can be done, the length of the rotation and the amount of area to be harvested each year would not have to be known. This is usually implemented by determining the long-run sustainable yield of an area based on computer-simulated yields. Inventories of stands determined by timber cruising are then used to delineate the area to be harvested each year. Because of differences in age and productivity of different acres, the harvest area will vary each year, while the harvested volume remains constant. Since the exact spatial distribution of the annual harvest is not known, there can be conflicts such as wildlife-habitat and visual-quality objectives, which extend over several continuous stands.

Area regulation can be very difficult to implement if the land productivity is not homogeneous, in which case simply cutting equal areas each year can lead to very uneven annual harvest volumes. Volume regulation is difficult to implement if the diameter distribution of the land is not regulated. There is the assumption that the annual harvest, as well as being equal in volume, will have an equal distribution of harvested diameters. Just as cutting the most productive areas in area regulation will reduce the growth rate for subsequent time periods, cutting the most productive diameters will reduce the future growth potential.

It is important to remember that using volume regulation does not imply that only uneven-aged management can be used. Volume regulation allows for making a sustained-yield unit out of a forest composed of almost any combination of patterns of even-aged, two-aged, balanced uneven-aged, and irregularly uneven-aged stands that might be desirable to satisfy other objectives. If it is most desirable to keep certain kinds of stands in the even-aged condition, it is still possible to have others elsewhere in the forest in an irregularly uneven-aged status without disrupting a sustained-yield program. The chief requirement is that all the stands of the whole sustained-yield unit in combination, conform to the appropriate distribution of diameter classes. Both of these methods of cutting regulations suffer from the inability to predict an account for large reductions caused by both biotic and abiotic disturbances, such as insect outbreaks, fires, and windstorms. These disturbances can be especially problematic when using the area method of regulation, because the disturbances are rarely distributed equally throughout the total area to be managed.

Global and National Trends in Industrial Plantation Forestry

Estimates at present suggest that there are about 670 million acres (270 million hectares) of plantation throughout the world (Lindquist *et al*., 2012). This includes about 6.5% of forest cover. It is predicted that by 2020 there will be 740 million acres (300 million hectares) of planted forest worldwide. China, the US, Canada, and India, in that order, are responsible for increasing the plantation area which has been growing by 7–15 million acres (3–6 million hectares) every 5 years (Lindquist *et al*., 2012). Of this new plantation land, 75% is for industrial timber production. The majority of the largest sawtimber companies of the world are from Canada and the US (Table 30.1), whereas the majority of the pulp and fiber companies are based in Asia and Scandinavia (Table 30.2). However, unlike most other regions, ownership of timber land in the US has dramatically changed since the 1990s (Box 30.1). It is clear that in most regions, especially in developed nations, industrial roundwood has shifted from being exploited from natural forests to

Table 30.1 Companies with the largest sawtimber production in the world.

Rank	Company	Production or capacity (m^3/yr)
1	West Fraser Timber Co Ltd (Canada/USA)	7,900,000
2	Canfor (Canada/USA)	6,900,000
3	Weyerhaeuser (USA/Canada)	6,449,000
4	Stora Enso (Finland)	5,960,000
5	Georgia Pacific (USA)	4,300,000
6	Ilim Timber (Germany/Russia)	3,900,000
7	Resolute Forest Products (Canada)	3,850,000
8	Tolko Industries Ltd (Canada)	3,800,000
9	Sierra Pacific Industries (USA)	3,200,000
10	Hamton Affiliates (Canada)	3,100,000
11	Interfor (Canada/USA)	3,030,000
12	Arauco (Chile)	2,800,000

Source: Adapted from The Sawmill Data Base: www.sawmilldatabase.com/productiontoplist.php

being produced in plantations. Most plantations include a handful of species that are mostly exotic to the planting site and with a narrow genetic base for superior growth, but susceptible to other unpredictable agents such as winds, ice-storms, drought, insects, and disease. In prior chapters, species lists of plantation species have been described (see Chapter 16).

Many arguments have been made that the global shift toward plantations for wood products is saving the exploitation of natural forests. Intensively managed plantations can utilize smaller areas and produce greater, more uniform yields. They produce more wood faster on smaller areas (Sedjo, 1983; Binkley, 1997; Sedjo and Botkin, 1997; Yin and Sedjo, 2001; Binkley, 2005). The logic of this argument supposes that there are no other external forces on natural forests, such as land clearance for agriculture or urbanization, and that countries with extensive natural forests will import cheaper wood from countries that produce it in plantations.

Plantations for the future must produce financially viable products but be ecologically sustainable in the long term. Currently, timber and pulp production is intensively managed to ensure full stocking of desired tree species, free of competition, disease, and insects.

Table 30.2 The world's largest wood fiber-producing companies.

Rank	Company Group	Country	Production in 2015 (1,000 ton)	Rank by Sales
1	Asia Pulp and Paper	Indonesia/China	19,000	1
1	International Paper	United States	11,922	1
2	Stora Enso	Finland	10,812	3
3	UPM	Finland	9,914	7
4	Svenska Cellulosa Aktiebolaget	Sweden	8,948	6
5	Smurfit Kappa Group	Ireland	7,650	9
6	Nippon Paper	Japan	7,292	5
7	Nine Dragons Paper	China	7,280	31
8	Sappi	South Africa	6,900	11
9	Oji Paper	Japan	6,861	4
10	Smurfit-Stone Container	United States	5,896	13
11	Abitibi Bowater	Canada	5,318	20
12	NewPage	United States	4,400	23
13	Norske Skog	Norway	3,998	30
14	Mondi	United Kingdom/South Africa	3,697	10
15	Temple-Inland	United States	3,660	28
16	Lee & Man Paper	China	3,500	46
17	Domtar	Canada	3,482	15
18	Shandong Chenming Paper Holdings	China	3,350	35
19	Cascades	Canada	3,330	22
20	Siam Cement (SCC)	Thailand	3,191	51

Source: Adapted from The Pulp and Paper Industry, Wikipedia: https://en.wikipedia.org/wiki/Pulp_and_paper_industry.

Box 30.1 Industrial land ownership change in the US 1990–2015.

Industrial timberland ownership in the United States has declined markedly between 1990 and 2015. Originally, industrial ownership amounted to between 9 and 17% of productive forestland (Society of American Foresters, 2006). Now ownership is a fraction of this amount with over 23 million acres (9.3 million hectares) sold between 2000 and 2004 to timberland investment management organizations (TIMOs) (Wilent, 2004) (Table 1). Weyerhaeuser was one company that largely held onto its land base. Reasons for this shift were multiple: (1) timber could easily be procured from lands that were not owned by the company; (2) timber lands were undervalued and susceptible to be sold off by corporate raiders who wanted to make a profit from acquiring companies; and (3) the tax code for companies was at a disadvantage to other landowning organizations such as real estate investment trusts (REITs).

Box 30.1 Table 1 Land ownership changes in the US as of 2015.

Timberland companies that sold their land	Timberland companies that retained their land	Timberland companies that changed to REITs	Timberland companies that changed to TIMOs
Boise Cascade	Bowater	Longview Fiber	Green Cow
Cavenham Industries	Gulf States Paper Corp.	Plum Creek	Hancock Timber Resources
Champion International	MeadWestvaco	Potlatch	The Forestland Group
Crown Zellerbach	Roseburg Forest Products	Rayonier	The Lyme Timber Company
Diamond International	Seneca	Weyerheauser	Molpus Woodland Group
Georgia-Pacific	Sierra Pacific		Campbell Group
International Paper	Simpson		Conservation Forestry
James River Corporation	Temple-Inland		TimberCorp.
Louisiana Pacific			Timberland Investment Resources
MacMillan Bloedel			
Scott Paper			
Stone Container Corp.			
St. Regis			
Union Camp			
Willamette Industries			

Source: Adapted from Wilent, 2004, and from Society of American Foresters, 2006.

This means intensive site preparation to remove stumps and impediments to planting, planting species with specific desired genetic traits, controlling spacing with initial plant spacing, and exclusion of all competitors (other woody and herbaceous plants) by applications of herbicide at the time of planting and at intervals thereafter. Fertilizers, mostly nitrogen, are commonly applied at intervals to increase foliage and growth. Some companies live-prune to ensure high-quality sawtimber and to ensure no loose or black knots in the lumber; other companies and landowners prune the dead limbs after crown recession upwards. Thinnings are done routinely for sawtimber plantations with usually two entries, the first for pulp or fiber and the second for small-diameter sawtimber before final harvest. Pulpwood and fiber plantations are usually planted at the spacing that they are cut at for final harvest, and receive no thinnings.

Most of the seed stock is obtained from genetically improved seed orchards and clonal gardens that have been propagated in intensive containerized operations. High financial returns for both timber and pulpwood are the incentives for these intensive and costly investments. Careful analysis must be done to demonstrate increased yield through intensive management does lead to increased profits. For landowners not tied to increasing yields, the profit margin can be the same for a less intensive management regime with lower yields and but also lower costs. The two major areas providing timber in the US are the loblolly pine region of the southeast (Cubbage *et al.*, 2007) (Box 30.2) and the Pacific Northwest (Murphy *et al.*, 2005). Public land in the US provides only a small amount of the Pacific Northwest timber harvest (Binkley *et al.*, 2005). The other industrial forest regions of the world include British Columbia (Canada), Scandinavia, southwest Chile, Atlantic southeast Brazil, Sumatra

Box 30.2 Managing loblolly pine for intensive sawtimber production: The Weyerhaeuser Company.

The Weyerhaeuser Company owns about 7 million acres (2.8 million hectares) primarily in the Pacific Northwest and the southern United States, and in Uruguay. It also has management rights to another 14 million acres (5.7 million hectares) in western Canada (Bigelow, Ewing, and Kumar, 2015). Weyerhaeuser has been at the forefront of intensive management of timber plantations. In particular, its operations in the southeastern US have focused on loblolly pine (Fig. 1) with investment returns routinely over 10%. Weyerhaeuser owns 540,000 acres (220,000 ha) on the coastal plains of North Carolina (Bigelow, Ewing, and Kumar, 2015). It also operates mills nearby in New Bern, Greenville, and Plymouth where about 594 million board-feet (1.4 million m^3) of sawtimber are produced annually. The company practices high-yield forestry (HYF) which includes intensive site preparation on drained lands, use of genetically superior seedlings spaced carefully to control for stocking, trees that are pruned with vegetation control, and fertilization applied at periodic intervals. Raised beds are the main site-preparation technique with use of pre-emergent herbicide. The main fertilizer used is a phosphate-coated urea to promote high growth on strongly organic soils. The use of drainage ditches preceded the Clean Water Act of 1972. No new drainage ditches are allowed but the original ditches have been grandfathered in and can be maintained.

Box 30.2 Figure 1 Loblolly pine plantations of different age classes that are managed on short rotation, imbedded in streamside management zones (SMZs) that include the reserve system of hardwoods on its land-holdings in North Carolina. The plantation in the foreground has undergone a recent row thinning. *Source:* Yale School of Forestry and Environmental Studies.

(Indonesia), Siberian Russia and northeast China. However, some of these regions rely upon their sheer size of forest area rather than the intensity of their management regimes (British Columbia, Siberian Russia).

The Development of Pine Plantation Silviculture in the US Southeast

The most intensively managed forest lands in North America are in the southeast US. They cover over 30 million acres (12 million hectares) of plantations comprising mostly slash and loblolly pine. This is currently the wood basket of the US. Like much of the lands in eastern North America, the agricultural lands of the south were abandoned over a period of years starting after the Civil War and continuing into the early part of the 1900s. The lands grew back to old-field pine and second-growth hardwoods for a variety of reasons that include a decline in soil productivity, a weakening of markets for agricultural cash crops, and increased insects and disease on agricultural crops, such as the boll weevil. Because of this, it became an important timber-producing region within the US during the first decades of the 1900s, supplying wood to the newly industrialized northeast. However, this production declined with the depression. It was only after World War II, with the GI Bill and the suburbanization and spread of new housing around America's cities, that the southern US looked promising as an area in land investment. Assessments were made at this period that there were 16–30 million acres of land that could be reforested. In 1952 there were 1.8 million acres of pine plantation; currently there are over 32 million acres (Fox *et al.*, 2007) (Fig. 30.2).

During the early years of intentional reforestation by planting after World War II, much of this was incentivized by the government Soil Bank Program that promoted the conversion of unproductive agricultural land back into forest. In addition, US Forest Service research focused on the technologies of nursery propagation and seedling planting during this time. Combined, these two government programs of research and land-conversion incentives promoted the first in a series of reforestation

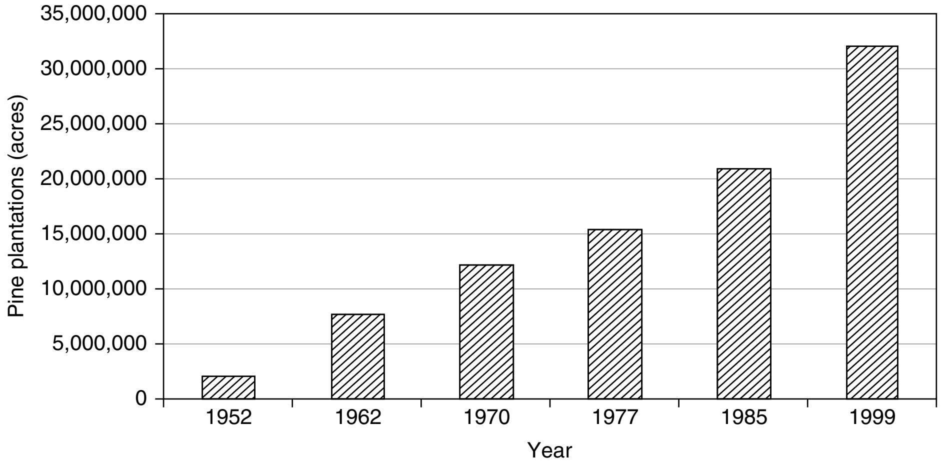

Figure 30.2 Number of acres of pine plantations over time in the US southeast. *Source:* Fox *et al*., 2007.

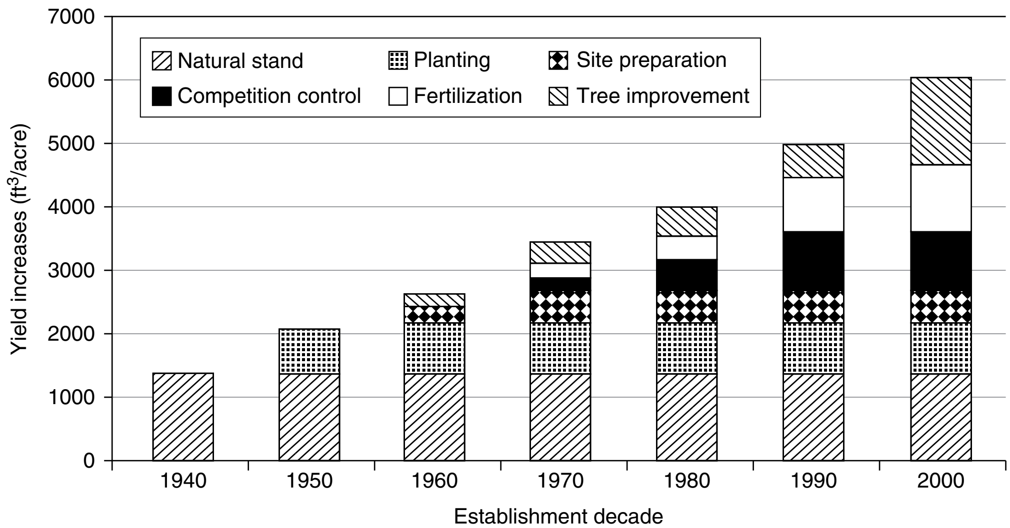

Figure 30.3 Yield increases per acre over time, with increased intensification of plantation management and continued development of improved techniques in tree improvement, competition control, site preparation, and fertilization. *Source:* Fox *et al*., 2007.

practices that intensified plantation practice. In the 1960s the Forest Service started on programs of genetic improvement of planting stock. Plantations established best on old fields compared to cutover stands because of higher hardwood competition on the cutover sites. More intensive site-preparation treatments that drum-chopped and burned the slash and hardwood competition, and scarified the soil, improved plantation establishment on cutover sites. Mistakes were made when soil fertility was further impoverished when the slash was windrowed or piled and then burned, instead of chopped and scattered. On other sites, Savannah plows were used, that were deep enough to break up sub-soil compaction of hardpans that had developed from agricultural activities on heavy clay soils. Such techniques improved soil aeration and rooting depths for increased plantation productivity. Similarly during this period (1960–1980) many of the poorly drained soils of coastal plains in the southern US were drained and planted to pine. Pine did not establish well on such sites because the soils remained waterlogged until the young plantations could change the surface soil aeration by transpiration. No new coastal lands are drained currently, but those that were in the past have been grandfathered into continued plantation forestry. The use of plows and raised bedding techniques were developed as a solution for planting on water-saturated soils.

Since the 1980s, continued improvements in productivity of plantation management have increased growth and yields fourfold from the original plantations of the 1940s, and shortened rotations by at least half (Fig. 30.3). In addition to improved site-preparation techniques

and continued genetic improvements, researchers recognize the importance of herbicides to control both grass and herbaceous and hardwood competition, and the use of phosphorus and nitrogen fertilizers, especially on poorly drained clay soils, both soon after plantation establishment and mid-rotation. Current methods include site-specific genotypes, fertilizer applications, and specific and timely use of herbicides, which all consist of a much more sophisticated and more productive plantation-management scheme than what was started after World War II.

Short-Rotation Forestry

In many parts of the world, short-rotation intensive forest management for wood products (especially pulp and paper) is practiced on the most productive sites. This type of silviculture usually involves high capital investment and necessitates the need to use trees with very rapid juvenile growth in order to recover these costs quickly. High financial returns on timber production are the driving force for creating these plantations, which are called **intensively managed forest plantations** (IMPFs) in the Mississippi Delta region and on irrigated land in the West (de Moraes Goncalves *et al*., 2014).

Plantations are established using two or three genotypes from genetically improved trees that have been cloned. Very intensive site preparation, including fertilizer and chemical weed control, are used, and the trees are grown on rotations as short as 7 years. In other parts of the world, species such as poplars, acacia, and eucalyptus are grown in the same manner, or in many cases even more intensively (see Box 30.3). These very short rotations can justify the very high capital investments. In addition, harvesting is highly mechanized and these intensive plantations are only established in close proximity to the mills, which keeps transportation costs to a minimum.

Box 30.3 Short-rotation fiber plantations from emerging producers: examples from Brazil and Indonesia.

Brazil

The former Atlantic forest region stretches for over 700 miles (1100 km) along the coast from Uruguay and the northeast tip of Argentina to the northeast corner of Brazil (Recife). Most of the forest had been cleared for agriculture when the countries were originally colonized, primarily by the Portuguese. Much of the agriculture now cannot be sustained, and reforestation has been a national issue. Over 12 million acres (5 million ha) of mostly former agricultural land has been reforested with fast-growing eucalyptus for short-fiber pulp to produce paper (Colodette, Gomes, and Gomes, 2012). The largest companies producing eucalyptus pulp are Klabin, Suzano Papel, Irani, Veracel, and Fibria. They are all located within different coastal regions of Atlantic Brazil. Plantations are by law within a mosaic of native forest reserves and riparian areas that must be at least 20% of the land. Planted at a 6 × 6 ft (2 × 2 m) grid with intensive site treatment, the use of herbicides to reduce herbaceous weed growth, and the use of fertilizer, these trees can be grown on 7–10-year rotations for pulp. Current annual productivity for plantations is about 7.5 thousand board-feet per acre (44 m^3/ha) per year. Current site-preparation techniques try to minimize compaction, burning, and bedding, but then require increased fertilization. Usually, no intermediate thinning is done unless remaining target crop trees are identified for sawtimber.

Indonesia

The island of Sumatra, and more specifically Riau Province, is Indonesia's primary producer of short fiber pulp. Most of this is from short-rotation *Acacia mangium* plantations. However, their origins are considerably more controversial than those plantations in coastal Brazil. The lands being cleared are existing native rainforest lands that have been logged and belong to the nation, but have been deemed by the government as "degraded." Much of this is peat swamp that is subsequently drained (Fig. 1), and much of the land has tenure conflict with local peoples. Originally, most of the pulp used was from the actual forest clearance process, not from the plantation which is mostly only just beginning to mature. It is hard to believe that in the space of 20 years, companies like Asia Pulp and Paper (APP) and Asia Pacific Resources International Holdings Ltd (APRIL) have literally transformed Sumatra's forest to intensive plantation agriculture. They represent about 80% of pulp and paper production for the country. Asia Pulp and Paper is a subsidiary of the Chinese–Indonesian conglomerate Sinar Mas Group which also owns and operates the palm oil company Smart PT. In 2014, pulp production was over 8 million short tons per year on about 17 million acres

Box 30.3 (Continued)

(a)

(b)

Box 30.3 Figure 1 (a, b) Photographs of peat swamp rainforest in Sumatra, Indonesia, drained and converted to *Acacia mangium* plantation. This land conversion has accelerated the loss of stored carbon within the peat and reduced the area of native peat swamp forest by over 90% throughout tropical Southeast Asia. *Source:* **(a, b)** R. Butler 2015. Reproduced with permission from Rhett Butler/mongabay.com.

(7 million ha). Acacia is intensively managed by site preparation, and use of herbicide and fertilization on 7-year rotations. Annual productivity is not nearly as high as that in Brazil partly because the soils are much poorer (peat) and partly because management and expertise are more variable.

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Application of Silviculture to Agroforestry

The basic human needs of food, shelter, and fuel, are often supplied by separate systems of land management: building materials and fuelwood are harvested from forests, food is produced from fields of herbaceous crops, fruit orchards, and livestock is from grazing in pastures. However, this has not always been the case and it is not always that way. When trees are mixed on the same land with food crops or pasture for domestic animals, the term **agroforestry** is used to describe the management system. This term has been in use for about 40 years, but the practices that it describes are much older. Agroforestry was a traditional practice used throughout the world that has been "re-invented" for current circumstances; it is a natural stage in the development of subsistence agriculture, often resulting from the partial clearing of natural forests and the desire to obtain a variety of products from a small plot of land. At least one agroforestry practice, the temporary growing of food crops between tree seedlings in young forest plantations, was part of organized silviculture since the early 19th century, but scientific agriculture and forestry have for the most part developed along separate lines. Only since the 1970s with the creation of ICRAF (The International Council for Research in Agroforestry) has there been widespread recognition that agroforestry has a role to play in modern silvicultural practice (Garrity, 2004). Research and application of agroforestry practices have developed to the extent that proceedings of international symposia are available (Jarvis, 1991; MacDicken and Vergara, 1990), scientific journals are devoted solely to the topic, and several comprehensive overviews of the field have been written (Nair, 1993; Montagnini *et al*., 2015).

Introduction

Much of the impetus for the modern development of agroforestry practice has arisen from problems with the declining productivity of croplands in the humid and semi-arid tropics. In the humid tropics, the lack of seasonal fluctuation in climate with high temperature and plentiful rainfall allows biological and chemical processes to occur rapidly, with potentially high levels of plant productivity. However, these same factors of consistently favorable growing conditions also impose limitations on the ability to sustain high agricultural productivity on a given plot of land (Ewel, 1986). The deep weathering of soils and rapid leaching caused by heavy precipitation mean that nutrients are soon depleted when forests are cleared and soils are tilled for agriculture, and they cannot readily be replaced by weathering of rocks. In addition, pest populations and weeds often build up to a greater extent than in temperate climates because there is no cessation of plant growth in harsh winter conditions (Montagnini and Jordan, 2005).

The traditional system of agriculture used originally across both temperate and tropical forest climates is called **swidden agriculture** or **shifting cultivation**. It has been derogatorily termed "slash and burn". The natural forest vegetation is cut and burned, and a crop such as maize or beans is grown for two or three cycles, and then the area is left fallow. Forest vegetation is allowed to develop, and soil nutrient stocks build up from atmospheric inputs, and, in the case of nitrogen, from biological fixation. The native populations of soil organisms recover, and insects, fungi, and other pest species decline with the absence of their crop hosts. The developing tree canopy also shades out agricultural weeds. Food is grown on alternate plots until the fallow site has been restored to a condition suitable for clearing and cropping again. The ratio of fallow period to cropping period that is needed on a site, varies with climate and soil conditions but is frequently on the order of 10:1 (Ramakrishnan *et al*., 1992; Cairns and Garrity, 1999). Thus, this system requires a good deal of land.

Swidden cultivation can be sustainable where human population densities are low. However, when the land base for food production is limited due to human population growth or the effects of land-distribution policies, fallow periods must be shortened to the point where they no longer serve their purpose and agricultural yields decline.

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The basic idea of agroforestry in such cases is to use the stabilizing aspects of the natural forest structure and function by mixing trees with herbaceous crops. The goal is to use the deep rooting and perennial nature of trees to maintain nutrient cycling and to mitigate extremes of climate, and thus increase crop productivity, lengthen the time that crops can be grown on a given piece of land, or both in combination, ideally making agriculture permanently sustainable on a site.

Such problems are not restricted to tropical rainforest climates, but extend to tropical savannas where seasonally heavy rainfalls, winds, or extremes in temperature can create many of the same problems. Temperate forest ecosystems are not entirely different, but the effects are reduced in degree by differences in climate and soils. If chemical fertilizers and pest-control measures were not available for large-scale commercial food production in most countries of the temperate region, the use of fallows or other agroforestry practices would likely become more important there. Indeed, the use of tree-dominated fallows was part of traditional subsistence agriculture in temperate as well as tropical regions for thousands of years in many parts of the world.

Agroforestry practices of a quite different kind have been developed in semi-arid regions of the world. Low precipitation restricts trees from developing a full canopy in these regions, and the natural vegetation is generally a mix of trees and herbaceous vegetation. Frequent fires and the grazing of large herbivores naturally adapted to these ecosystems cause grasses to dominate among the herbaceous species. Combining management of stands of trees for sawtimber and fuelwood with pasture for livestock is a logical approach to making maximum use of the structure of the natural vegetation.

In the last decade, agroforestry systems have been promoted as a means to integrate trees within agricultural systems that create additional benefits besides increasing agricultural productivity with supplementary protection value (soil conservation, fertility improvement) and utility value (timber, fuelwood, fodder). Current studies are showing the benefits of increased carbon sequestration, watershed protection, and biodiversity conservation (Jose, 2009). For example, carbon storage is an additional benefit both as aboveground in the living biomass of trees and belowground in the soil (Albrecht and Kandji, 2003). Estimates of carbon sequestration range from 9 Mg/ha in semi-arid climates, to over 63 Mg/ha in moist temperate regions (Montagnini and Nair, 2004). Other work in central America has demonstrated the value of agroforestry systems for conservation of resident wildlife diversity and migratory passerines in particular (Harvey and Haber, 1998; Harvey and Vilalobos, 2007; Schroth and Harvey, 2007; Perfecto *et al.*, 1996).

Stages of Stand Development and Agroforestry

Any system that aims to combine food crops or pasture with trees must deal with the inherent problem of the competitive interactions that exist between the different plant lifeforms (Anderson and Sinclair, 1993). As the tree layer increases in density, its canopy and roots dominate light, water, and nutrient resources, and understory plant production then declines. Competition for light between trees and understory is often the most critical factor because it is clearly one-sided. Many staple food crops are herbaceous plants that are low in stature with relatively low shade tolerance, and cannot survive in forest understories. Even the more shade-tolerant shrub and vine crops decline in productivity with increasing overhead shade. Agroforestry can thus be categorized as **successional** (allowing competition to occur and progress in changing plant composition) or **permanent** (continuously fighting against competition and promoting the same plant composition over time).

Successional Agroforestry Systems

Because of competition, agroforestry systems must take advantage of stages in forest stand development (described in Chapter 4) in which the tree canopy does not completely dominate site resources. A brief but highly productive period for crops occurs in the stand-initiation stage when the tree seedlings and sprouts do not form a complete canopy. As a dense canopy forms in the stem-exclusion stage, there is little opportunity for growing plants of low stature. Later, as the canopy rises in height in the understory-reinitiation stage, growing space exists for crops in the diffuse light that reaches the ground level. The swidden systems originally practiced throughout the world's forests are the original examples of successional systems using the principles of stand dynamics (Raintree and Warner, 1986).

This pattern is illustrated at present by the commercial intercropping practices used with plantations of coconut palms, described by Nair (1993). In the first 8 years after planting, many shade-intolerant crops, such as maize, rice, or peanuts, can be grown between the young palms. The shade of the dense palm canopy from about age 8–25 years precludes intercropping, but after that period, moderately shade-tolerant species can then be grown beneath the taller palm canopy, including cassava and cacao in the understory and black pepper vines on the palm stems. The small rooting area of mature palms helps limit the belowground competition with these crop plants. These systems are sophisticated to manage both in terms of silviculture and in terms of responding to markets for different products over time. They are more resilient to the volatility of prices for a single commercial

species, and they provide higher ecosystem service benefits in carbon sequestration, watershed protection, and biodiversity, than permanent agroforestry systems (see below). They are most applicable to soils that are marginal in fertility and where native systems are intricate and complex (tropical rain forests). These natural systems are exposed to ever-present pests and diseases, and counter these factors by density dependence and chemical protection (Ewel, 1999).

Greater opportunity exists to grow crops beneath trees in dry climates where canopies are not as dense, but it is necessary in nearly all climates to reduce tree density below that of natural stands in order to shift a substantial portion of the growing space to crops, even during the stand-initiation or understory-reinitiation stages. It is possible to maintain crops during the stem-exclusion stage by thinning the overstory, essentially creating conditions for understory reinitiation at an artificially early age. In a sense, much of agroforestry can be understood as the manipulation of the stages of stand development so that plants of other lifeforms can be grown, although the complexities of carrying this out are enormous.

Permanent Agroforestry Systems

There are plenty of examples in agroforestry where stand development stages are deliberately maintained within one stage of development. Such systems are the norm, primarily because they have arisen from a modern day agricultural and sedentary construct, in which plants and their combinations are kept in check by frequent pruning, weeding, and thinning, to maintain the same growing space consistently for each crop and individual. Doing this will provide the same crop product and yield over time. This can be very desirable in maintaining a simple routine for cultivation, where single crops have strong markets all the time. Taking this approach can be risky where markets are volatile, where social values are unpredictable, and where marginal lands are prone to drought, pests, and disease (Ewel, 1999).

The most obvious and dramatic examples of this are commercial agricultural operations for coffee, tea, and cacao, which are maintained through continuous pruning and fertilization to conform to the same growing space at the time of planting. The shade trees that are used are widely spaced and pruned at periodic intervals. Other examples are those systems that are maintained for intensive cattle pastures, or where arable crops are cultivated every year.

Classification of Silvicultural Systems within Agroforestry

Silvicultural systems within agroforestry must be developed for each set of ecological, economic, and social conditions. They consist of modifications and combinations of a relatively small set of practices. Classifications of agroforestry practices have recognized distinctions between those practices combining trees with food crops (herbs, vines, or shrubs), which are used in **agri-silvicultural systems**, and combining trees with pasture and livestock, which are used in **silvipastoral systems**. There are also systems of **shelterbelts** and **hedgerows** which are devised specifically to prevent erosion that occurs from tilling soil for crops or sheltering livestock (Nair, 1985). Such examples are called "complementary" in agroforestry because they complement other land uses (e.g., hedgerows, live-fences, riparian buffers, shelterbelts, windbreaks).

Agri-silvicultural systems can be categorized as either **successional** or **permanent**. Successional systems are **swiddens** and their modern-day equivalents that utilize **improved fallow** periods, and that accommodate some form and variant of stand dynamics. These include **multistory home gardens** or **tree gardens** which are continuously changing and growing with multiple age classes.

Permanent systems are those that utilize **shade tree/crop combinations** that do not change over time, **alley cropping** where the trees are planted in rows and the agricultural crops are planted in between, **silvopastoral systems**, and **shelterbelts**. The basic principles of these practices are presented in this chapter, based largely upon the descriptions of Nair (1993).

Successional Agri-silvicultural Practices

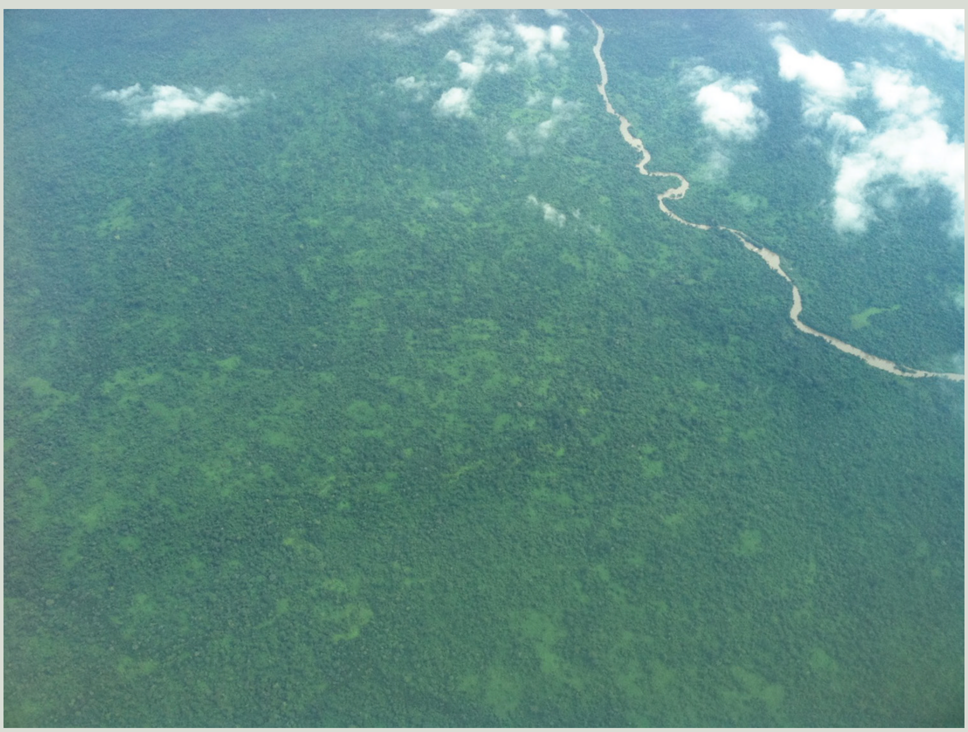
Swidden Agricultural Systems

Dove (1983) outlines the myths that have been traditionally held around swidden agriculture. The first myth is that swiddens are usually not communal but are owned and worked by households and families; the second myth is that the practice is wasteful and degrading of the soil when in fact the long forest fallows rejuvenate the soil, replenishing nutrients; and the last myth is that swiddens are exclusively managed for subsistence when in fact market-oriented cash crops are grown when opportunities arise. Swidden systems can be thought of as the original agroforestry systems of forest peoples. Many indigenous peoples still practice complex examples, such as the Kayapo of the Amazon, Brazil (Posey, 1985; Parker, 1992), the Bari of northern Colombia (Beckerman, 1983) (Box 31.1), and the Bora of the upper Amazon, Peru (Denevan and Padoch, 1987; Denevan and Treacy, 1987). Studies have shown that even in the most pristine of rainforests, evidence of swidden agriculture, in charcoal and starch grains, from thousands of years ago persists in the soils (Piperno *et al.*, 2000).

Box 31.1 Bari swidden agriculture.

Swiddening is an agroforestry system that is strongly successional. All swiddens temporarily clear a patch of forest within which agricultural crops (manioc, upland rice, vegetables) are cultivated for a number of years before the weeds become too competitive and/or the soil becomes depleted of nutrients. Cultivation is then stopped and the patch returns back to forest (Fig. 1). The forest that comes back can often contain trees of economic use, and some of these may have been planted. This new forest can be thinned and products are harvested before the cycle repeats itself. For that reason, swidden is also called shifting cultivation. This practice of switching between agriculture and forest on one patch of land has been its downfall in modern day land-use planning (Padoch *et al*., 2007), where lands have been either demarcated for forestry or agriculture but not both (Agrawal and Sivaramakrishnan, 2001; Peluso and Vandergeest, 2001; van Noordwijk *et al*., 2008). This kind of planning was made particularly in forested biomes without serious consideration of what could or should be done if soils are not fertile enough to promote permanent and sedentary agriculture (Dove, 1983; Padoch *et al*., 2007).

The Bari swidden system is an example of a complex temporal and spatial agroforestry system. The Bari are an indigenous South American people found in the Maracaibo region that includes the northeast borderlands between Colombia and Venezuela. Bari swidden agroforestry systems delineate crops by an annual or temporal zonation, rather than mixing crops together at one time. This is unusual, as most swidden systems rely upon sequential intercropping of mixtures of crops (Beckerman, 1987, 2013). In Bari swiddens, patches are usually small, less than 2.4 acres (1 ha), and typically the newly made field is planted with squash, sweet potato, and many varieties of manioc in separate areas (Beckerman, 2013). After the main crop of manioc has been harvested on several annual rotations (about 3 years), bananas and plantains are cultivated and harvested over the next 3–6-year period. Afterwards, certain trees are interplanted such that by the 10th year, some of these trees are providing fruit. Once the weed growth has become impenetrable and difficult to cut back, the patch is abandoned to fallow. The fallow period after the final fruit tree crops have been harvested can last about 15 years before the land is cleared and the cultivation cycle resumes. Compared to other swidden systems, the Bari system is relatively simple and does not consist of a large diversity of crops (Beckerman, 2013). In other sections of this book, the Milpa swidden system of the Maya in the Yucatan, Mexico (Chapter 9) and the Yanomami of the Venezuelan and Brazilian Amazon (Chapter 1) have been described.



Box 31.1 Figure 1 An aerial depiction of the South American rainforest and the patchwork of swiddens within it. *Source:* Mark S. Ashton.

Swiddens are based on clearing a patch of natural forest, burning the slash, preparing the soil usually by scarification, and cultivating basic food crops that usually include corn, upland rice, manioc, or beans, either singly or in combination. Crops are either dibble-planted or seeds are scattered to utilize the flush of nutrients from burning the slash and disturbing the soil. These crops can be sustained for a period of time that is dependent upon the residual flush in soil fertility. Subsequent perennial short-lived plants are cultivated (e.g., plantains, bananas) with fruit and timber trees. Once the natural regeneration reclaims the opening, people come back to gather the fruits and cut the timber trees. There are many variants to this in terms of treatments and species combinations. The variations in swidden are associated with the forest type and the culture and economy of the people. At present, many regions' swiddens have hybridized with market-based systems that promote the harvest and sale of products such as coffee in Papua New Guinea (Bourke, 1985), charcoal in Peru (Padoch *et al.*, 1985), and rubber in Sumatra (Gouyon, de Foresta, and Levang, 1993).

Improved Fallow

The poor results of many agricultural trials that are caused by competition effects of differing plant growth habits, suggests that the use of a more direct modification of swidden (shifting) agriculture, the idea of **improved fallows** may be more successful in some conditions. Rather than mixing crops and trees spatially, crops are grown in monocultures for several cycles, followed by a fallow period in which the vegetation is managed to improve the efficiency of ecological restoration. By planting tree species with rapid growth, deep rooting, and nitrogen-fixing symbioses, it may be possible to restore the fertility of soil and shade out the light-demanding weeds in a short time. In some soil and climatic conditions, fallow periods of 2 years or less may maintain soil fertility (Sanchez, 1995, 1999). Even with longer periods of 5 years or more, there are advantages in using woody species rather than herbaceous species because the economic value of the fallow land can be maintained by planting tree species that produce fuelwood, fodder, or fruit or nut crops. Also, weeds can be suppressed by tree shade, and soil bulk density can decrease and infiltration capacity increase, thus restoring water-holding capacity. Soils with low base cations usually require longer fallow periods (greater than 5 to 15 years) to build nutrients back into the soil (Szott, Palm, and Buresh, 1999). This is not so necessary on soils with high base cations and where nitrogen is the chief limiting factor. Examples of species used for improved fallows include *Tithonia diversifolia* (a composite native to Central America) in western Kenya (Jama *et al.*, 2000), *Sesbania sesban* (a legume native to Central America) in eastern Zambia (Kwesiga *et al.*, 1999), *Acacia nilotica* in central India (Pandey and Sharma, 2003), and with *Inga edulis* and *Colubrina glandulosa* in the Peruvian Amazon (Alegre *et al.*, 2005). *Acacia nilotica* increased arable crop yields of upland rice by over 75% the first year and had legacy yield increases for over 5 years (Pandey and Sharma, 2003).

Taungya

The temporary intercropping of herbaceous crops in the establishment phase of a forest stand, known as **taungya**, has somewhat more complicated economic objectives because the trees and crops usually have different owners. The system was devised in southeast Asia in the 19th century to help establish government-owned teak plantations (Wiersum, 1982). Local farmers were allowed to take advantage of the vacant growing space between young teak trees, and so they gained usable farm land. In the process of weeding the crop plants, they also freed the tree seedlings of competition. The forest owners received the benefit of intensive weed control in their plantations, as well as any fees charged for the use of the land which helped offset establishment costs. The practice of taungya has proven very successful and is now a common method for establishing plantations throughout the tropics, with varying tree and crop ownership patterns.

Although the practice of taungya is temporary on any piece of land, it has served as a step in the development of more permanent agri-silvicultural systems. For example, taungya was initially used in Indonesia only during the first 2–3 years of teak plantation growth, when farmers grew maize and dryland rice crops. When government policies shifted to better benefit local people, taungya farmers were allowed to plant fruit and other multipurpose trees on 20% of the area, and carry them through the full rotation, thus creating a structure approaching a multistory tree garden (Kartasubrata and Wiersum, 1995).

The taungya approach is used on a limited basis in temperate forests and represents one of the few examples of agri-silviculture in North America. In eastern Canada, corn, soybeans, and other crops have been planted for the first few years in hybrid poplar plantations, which are grown on a 15-year rotation for pulpwood (Gold and Hanover, 1987). Considerable research has been done with the use of agroforestry to improve the financial aspects of establishing black walnut plantations for nut and timber production. Wheat or soybeans are grown

between widely planted rows of walnut trees for the first 10 years, and after the intensity of shading increases, livestock forage is produced for another decade. The effects of wide spacing of walnut trees are countered by pruning lower branches to improve timber quality. Nut harvesting begins at about age 15 and continues to the end of the timber rotation at age 60–80 (Garrett and Kurtz, 1983; Campbell, Lottes, and Dawson, 1991).

Multistory Tree Gardens

Tree gardens are small plots that are often developed as a "homegarden" located around a farmhouse. They are characterized by a large variety of tree species, shrubs, and vines, but with few or no herbaceous crops except in the immediate surroundings of the house. The main purpose is the production of food for household consumption, so the plots range from only a fraction of an acre to about 2 acres (~1 ha). The best-known examples of homegardens are those of south and southeast Asia, but they are common in Central America, Africa, and other regions as well. Examples from studies done in Asia include the Kandyan home gardens of Sri Lanka (Jacob and Alles, 1987), the homestead gardens of Kerala, India (Nair and Sreedharan, 1986), homegardens in Central Sulawesi (Kehlenbeck and Maass, 2004), and the tree garden systems of West Sumatra, Indonesia (Michon, Mary, and Bompard, 1986). Studies reported for Africa and Central America comprise the Chagga home gardens of Mt. Kilimanjaro, Tanzania (Fernandes, Oktingati, and Maghembe, 1985), and the Mayan homegardens of Quintana Roo, Mexico (De Clerck and Negreros-Castillo, 2000).

Tree gardens can be demarcated into spatial zones that comprise the patio around the house, the early-successional vegetation that includes shrubs and pioneer vegetation, and the stratified tree garden. The three or four vegetation layers of the tree garden may consist of large emergent shade-intolerant trees as an upper canopy (e.g., coconut, durian, mahogany, kapok), a shade-tolerant canopy (mango, jak fruit), a subcanopy of understory trees (rambutan, mangosteen, cacao), and a shrub layer (gingers, aroids, yams). The canopy and subcanopy trees are mostly trees that produce a variety of fruits and spices (Box 31.2).

A closely related practice is the creation of "mixed tree gardens," which are generally located on the commonly held land of a village rather than around individual farmhouses. The structure is very similar to that of homegardens, but the herbaceous crops are usually not included. There is more emphasis on fuelwood and timber harvesting, mixed with production of fruits, nuts, medicines, and spices.

Of all agri-silvicultural practices, multistory tree gardens bear the closest resemblance in structure and function to that of stratified forest stands. Much of the photosynthate is used for maintenance respiration and synthesis of woody tissues, so food production is rather low. However, there is low risk of catastrophic pest problems, and tight control exists over nutrient cycling and erosion. Tree gardens can stay in continuous production for centuries. The key benefit is the diversity of food, fuel, and medicine products derived from a small plot. Tree gardens are usually only one component of a farm system in which staple foods (rice, wheat) are grown in separate fields, often as monocultures.

Box 31.2 Home garden systems in southwest Sri Lanka adjacent to the Sinharaja. A traditional Sinhala village.

Home gardens in southwest Sri Lanka are complex stratified agroforestry systems that are essentially private smallholder lands. They can be defined spatially with different management zones that include areas for early successional shrub cultivation of banana, papaya, and manioc, tree gardens that include canopy trees of coconut, jak tree, mango, and durian with subcanopy fruit trees of rambutan and mangosteen, and the yard around the home with flowers, medicinal herbs, and spices. These gardens are usually adjacent to the home and upslope of the paddy fields (Fig. 1). On the upward side of the home garden and house site, tea is commonly planted as a cash crop. In the past, the sloped land was kept in rainforest that was under swidden cultivation when the rice crop failed. Scholars believe these home gardens have been a cultivation practice for more than 25 centuries. In the central hill region of Sri Lanka these gardens evolved into spice gardens, primarily to trade spice to the Portuguese when the region was a Sri Lankan kingdom several centuries ago (DeSilva, 1981). They have become known as Kandyan Gardens after the capital city of this region (Jacob and Alles, 1987; Pushpakumara *et al*., 2012). This traditional mixed-forest/gardening system has been described as a diverse and economically viable form of land use (Jacob and Alles, 1987). Although centuries old, the home garden system has continued to evolve from one generation to the next in order to suit socio-economic, cultural, and ecological needs (Pushpakumara *et al*., 2012). Past studies have noted that the composition of home gardens depends on socio-economic conditions and strategies of the time and that crop and tree planting change with markets (Pushpakumara *et al*., 2012).

Box 31.2 (Continued)

Box 31.2 Figure 1 A landscape view of home gardens around homes in a Sri Lankan village. The paddy fields are in the foreground, tree gardens surround the homes while further upslope, patches of swidden and rainforest are visible. *Source:* Mark S. Ashton.

Permanent Agri-silvicultural Practices

Shade Tree/Agricultural Crop Combinations

A somewhat simpler practice is the management of **shade tree/crop combinations**. These are generally two-storied stands with one or more species of taller trees growing above an herbaceous, shrub, or small tree crop. In contrast to tree gardens, these are created for commercial crop production but are still used most commonly by small landowners. Examples in the wet tropics of crops grown beneath shade trees include cacao, coffee, tea, cardamom, and black pepper. All are shrubs or small trees which are at least moderately shade tolerant and originally from the natural forest understory. Examples in the drier tropics of understory crops include maize, millet, and sorghum, which are arable annuals, and grains that can be grown during the wet season. During the dry season, the shade trees can provide annual harvests of fodder, fuelwood, fruits, and nuts, either for income or subsistence. Shade trees are often chosen from among the native species of a region. If planted too densely, it is necessary to thin the overstory trees as the understory develops, and in so doing, fuelwood, poles, and sawtimber are produced.

The shade of the overstory canopy can be useful in reducing temperature and water loss in the crops below, but the shade trees often are more valuable for the role they play in nutrient cycling than for the shade they create. In some cases, the shade actually decreases yields of the understory crop (Campanha *et al.*, 2004). More often than not, the deep roots of the shade trees take up nutrients that have been leached from the upper soil layers or have been weathered from rocks in deep strata, and thus are unavailable to the shallow roots of crops. A portion of the nutrients becomes available to crop plants through shade-tree litterfall. The overstory trees are sometimes pruned at the start of the growing season (wet season) to reduce the shading effect and increase the rate of nutrient contribution of litter to the soil (Mafongoya, Giller, and Palm, 1997). Nitrogen-fixing trees are valuable as shade trees, because of the high nitrogen content of their foliage, but the litter decomposition rate and value for timber or fuelwood are equally important in selecting species. Some of the tree species that are most widely used as shade trees are nitrogen-fixing legumes from Central America such as *Gliricidia sepium*, *Leucaena leucocephala*, *Inga* spp., and *Erythrina* spp.

For the wet tropics, an example of a shade tree/crop combination used in Central America consists of coffee or cacao grown beneath valuable timber trees (*Terminalia ivorensis*, *Tabebuia rosea*, *Cordia alliodora*) (Fig. 31.1) (Beer, 1988; Somarriba and Beer, 2011). In this system, shading may have some beneficial effect for the small tree crops in the dry season, but the main effect of the

(a)

(b)

Figure 31.1 Examples of a shade tree/crop combinations. **(a)** Shade cacao growing beneath a high canopy of leguminous trees in Southern Bahia, Brazil. **(b)** Shade coffee beneath pollarded *Erythrina* trees in Costa Rica. *Source:* **(a, b)** Mark S. Ashton.

overstory shade is to decrease productivity during the long wet season. The value of the trees is in the maintenance of efficient nutrient cycling and in extra income from timber. When large commercial landowners grow coffee without shade trees, they compensate by adding chemical fertilizer (not shade cloth), to replace the effects of the overstory. Normally, coffee and cacao have leguminous shade trees (*Inga* spp., *Erythrina* spp.) in the overstory. These species do not produce good timber but are better contributors of soil fertility and fodder. The use of an *Alnus* shade-tree overstory to cultivate cardamom in India is an Asian example. *Alnus* fixes nitrogen, produces high amounts of easily decomposable litter, and together with the partial shade that it creates,

increases yields of cardamom more than twice as high, compared to cultivating cardamom in full sun (Sharma, Sharma, and Purohit, 1994).

Other shade trees used with understory crops like coffee, tea, or cacao are often also of commercial non-timber value, such as rubber (*Hevea brasiliensis*), coconut (*Cocos nucifera*), peach palm (*Bactris gasipaes*), and areca nut (*Areca catechu*) (Alvim and Nair, 1986). Shade trees must be carefully selected and spaced such that their crowns are deciduous, sparse, or are spaced far apart to ensure enough light for the understory crops during the growing season. Deep, large-crowned trees such as mango (*Mangifera indica*), jak fruit (*Artocarpus heterophylla*), or oil palm (*Elaeis guianensis*) are generally not good shade trees compatible with cultivating an understory.

For the dry tropics, an example in Ethiopia is the use of *Albizia albida* as a shade tree that is grown above crops of maize and sorghum (Poschen, 1986). Apart from a supply of fuelwood and fodder for livestock, the leaf mulch of *Albizia albida* increases crop yields by over 50%. Other dry tropical examples include the cultivation of millet beneath pruned *Parkia biglobosa* and *Vitellaria paradoxa* in Burkina Faso, West Africa (Kessler, 1992; Bayala, Teklehaimanot, and Ouedraogo, 2002), and the cultivation of beans, maize, and sorghum beneath selected naturally regenerated trees that are often pollarded or left to grow (e.g., *Cordia alliodora*) in the dry region of western Honduras (Hellin, William, and Cherrett, 1999).

Alley Cropping

Another agri-silvicultural practice, known as **alley cropping**, shares the same objective of using trees for their nutrient cycling effects, but it is used for growing light-demanding herbaceous food crops such as maize, cassava, and beans (Yamoah, Agboola, and Wilson, 1986). The annual crops are planted between hedgerows of trees that are maintained at only shrub size by repeated pruning of the trees in order to reduce the shading. The trees planted in rows include the legumes *Cassia* spp., *Gliricidia sepium*, *Flemingia* spp., and *Erythrina* spp. (Yamoah, Agboola, and Wilson, 1986; Schroth and Zech, 1995). The pruned branches from the hedgerow trees form a green mulch that is applied to the crops, improving the nutrient availability and organic matter content of the soil (Fig. 31.2).

Temperate agroforestry is much less developed than in the tropics but research is demonstrating the growing importance of alley cropping as a mechanism for maintaining the long-term sustainability of food systems (Gillespie *et al*., 2000; Tsonkova *et al*., 2012; Smith, Pearce, and Wolfe, 2013). In North America, alley cropping has been under trial in certain regions, with the most notable work in Ontario, Canada but also in Iowa, Indiana, Minnesota, and Georgia. There have been studies of the potential to increase carbon sequestration and soil fertility, and reduce climate warming from nitrous oxide gas emissions on marginal agricultural lands (Thevathasan and Gordon, 2004; Peichl *et al*., 2006). Trees used in intercropping trials were *Populus* spp., *Salix discolor*, *Acer saccharinum*, *Fraxinus americana*, *Corylus avellana*, and *Robinia pseudoacacia*. *Populus* hybrids increased carbon sequestration rates in soil over four times more than agricultural fields that had no intercropped tree plantings (Thevathasan and Gordon, 2004).

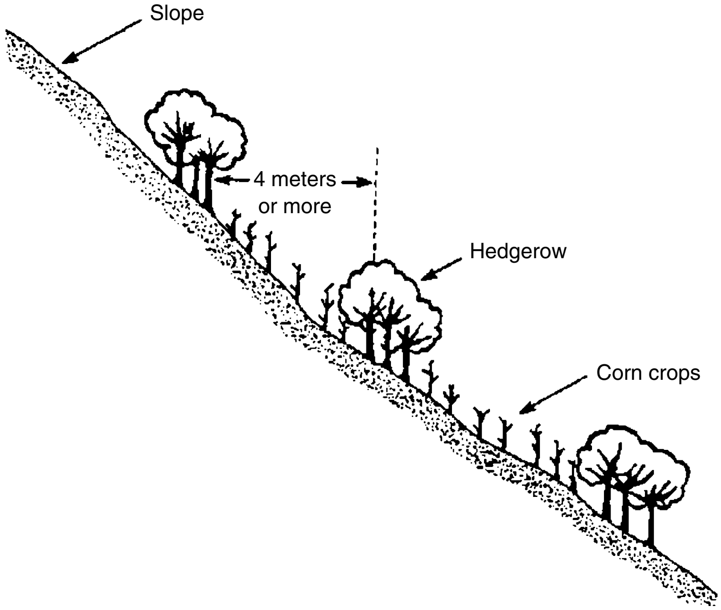
Alley cropping has received considerable attention in agroforestry research, but trials have given variable results with respect to increasing crop yields (Kang, 1993; Gillespie *et al*., 2000). The shading of the trees is sometimes too great, even with pruning, and moisture competition between tree and crop roots is problematic on dry sites. In many of these cases, the competitive effects can outweigh the benefits to soil fertility, resulting in lower crop yields than those obtained without the hedgerows of trees. The success of this practice is generally determined by the yield of the herbaceous crop alone, because it is usually impossible to harvest much from the hedgerows. It is often tempting to use the branches for livestock fodder, but this would defeat the nutrient-management objectives of the system. The practice is most useful in degraded areas where crops would not grow otherwise.

Silvipastoral Practices

Developing management methods that successfully combine livestock pasture with stands of trees can present even greater challenges than combining annual food crop production with trees. Not only can the shade from the tree canopy inhibit grasses and other forage plants, but the animals may also damage or destroy seedlings by browsing or trampling on them. Indeed, some of the most complete kinds of deforestation have resulted from the continued pasturing of goats and other livestock in forests of semiarid regions. Yet, with careful management, several advantages can be gained by combining these two production methods on the same land.

Some silvipastoral methods keep the animals separate from the trees in order to avoid the problems of interspecific plant competition and animal damage (Jose, Gillespie, and Pallardy, 2004). They include the planting of small stands of **fodder trees**, which are coppiced on short rotations, with the cut foliage being carried to livestock in adjacent stalls or pastures. The same practice can be used when fodder trees are grown as **live fence posts** along pasture borders, but the stems are cut at a height of about 6 ft (2 m) (a practice known

(a)



(b)

Figure 31.2 **(a)** A graphical image of an alley cropping system depicting the low coppice hedgerow and corn cultivation aligned across a slope to minimize soil erosion. *Source:* Adapted from Vergara, 1984. **(b)** Manioc and okra being cultivated between rows of woody shrubs. The hedges are periodically pruned and the branches are used as mulch for cultivating annual crops in the "alleys." Many other species combinations use the same arrangement. *Source:* IITA. Reproduced with permission from IITA.

as **pollarding**) to keep the young sprouts out of reach of animals and to preserve the utility of the stem as a fence post. Legume species are frequent choices for fodder trees because their foliage and pods are rich in nitrogen; for this reason, stands of these fodder trees are sometimes called protein banks.

There are two ideas behind silvipastoral systems. One is increasing the utility value to produce timber, fruits, nuts, or fuelwood from a stand of trees, while developing productive pasture for livestock in the understory. The second is to increase the productivity of the pasture grasses through the use of nitrogen-fixing legumes that also can increase fodder yields and quality.

Timber, Fuelwood, Fruits, and Nuts in Sivipastoral Systems

This is one of the few agroforestry practices that has been developed on at least as large a scale in the temperate zone as in the tropics. Grazing domesticated animals in dry woodlands or savannas, or in partially cleared

forests in wetter climates, was used throughout the world in the early history of agriculture (Long, 1993). Well-developed silvopastoral systems called **wood pastures** were used in medieval Europe, and their origin is certainly much older than that (Rackham, 1986) (see Chapter 12, coppice systems). The rights of various groups to use the land was complex; often the landowner held the rights to the timber, but local farmers had government-granted rights or paid fees for pasturing their animals and pollarding non-timber trees for fuelwood, fence posts, and fodder. Animals were fenced out of areas only when new trees were being established. Some of these wood-pastures were contained within "deer-parks" in which both native and exotic deer species were fenced, and supplied with supplemental water and winter feed. This transitional stage between wildlife management and livestock production was an important form of meat production in medieval Europe (Rackham, 1986). Some of these systems are still practiced, such as the "dehesa" system in the Mediterranean region of Spain, where cattle and sheep range freely in a savanna–oak complex including *Quercus ilex* (holm oak) and *Q. suber* (cork oak) (Joffre *et al*., 1988; Joffre, Rambal, and Ratte, 1999). Also, in northern and central Europe (The Netherlands, Belgium, France, and Germany), there is the "Streuobst" orchard where fruit and nut trees are cultivated within pastures grazed by livestock (Herzog, 1998). Trees species usually include apples (*Malus domestica*), pears (*Pyrus communis*), cherries (*Prunus avium*), walnuts (*Juglans regia*), almonds (*Prunus dulcis*), and chestnuts (*Castanea sativa*). In the tropics, the obvious example is the use of palms that provide edible fruits such as the babassu palm in pastures of northeast Brazil (May *et al*., 1985).

The main impetus for developing silvipastoral management remains similar to those ancient systems: to diversify production in a way that provides supplemental income to grazing fees. The forest land and the livestock often have different owners, which has at times been an impediment to the creation of efficient management schemes.

The opportunity to develop pasture vegetation during the various stages of stand development is similar to that for herbaceous crops. The most productive stage for shade-intolerant forage crops is during stand initiation; the closed canopy during stem exclusion precludes most herbaceous vegetation, and more shade-tolerant forage species develop during understory reinitiation. The main difference in this pattern is that the initiation stage, which is so useful for taungya cropping, is limited in value for pasture because of the problem of animals damaging tree seedlings. Thus, older stands with open canopies in dry climates are the most logical kind to use for grazing. In the western US and western Canada, for example, it has long been a practice to graze cattle and sheep in the unimproved native grasses that grow beneath ponderosa pine (*Pinus ponderosa*) and other conifers on the east side of the Cascade and Coastal Mountains (Adams, 1975). The main limitation to this practice is the need to restrict animals from regenerating stands and to space trees such that competition for soil water between grass and tree is minimized (Yunusa *et al*., 1995; Fernández *et al*., 2008). However, grazing and forestry are considered less compatible in the wetter climate on the west side of the mountains because stands form dense canopies that preclude herbaceous understories. However, there are more shade-tolerant grasses, such as *Brachiaria* spp., that can remain more productive beneath tree canopies (Wong, 1991).

The practice of grazing livestock in older stands can be used in wet temperate or tropical regions, only if stand density is reduced to a level below that which is normally used for timber production. This approach is used with widely spaced plantations of slash pine (*P. elliotti*) and longleaf pine (*P. palustris*) in Florida (Linnartz and Johnson, 1984; Lewis and Pearson, 1987) and of radiata pine (*P. radiata*) in New Zealand and Australia (Knowles, 1991). It may be necessary to establish plantations in clumped or multiple-row configurations, and to prune lower boles in order both to produce adequate forage yields and to develop acceptable wood volume production with good stem quality in these stands. In New Zealand, researchers have tested the incorporation of nitrogen-fixing groundcovers (e.g., lupins, clovers) with plantation trees such as *P. radiata* (Goh *et al*., 1996).

Grazing is also used in some situations as a silvicultural tool to release conifer seedlings from competing vegetation, because most conifers are less palatable than hardwoods and herbaceous plants (Fig. 31.3). This reduces the cost of weeding operations and is particularly useful on lands where it is not possible to use herbicides or prescribed fire. Considerable knowledge and care are required to use this technique without allowing damage to seedlings. The season and number of days of grazing must be controlled, which requires frequent moving of the animals. It may be advantageous to sow seed of crops to prevent the growth of dense brush; sheep and cattle can maintain low herbaceous vegetation more efficiently, and are less likely to browse the conifers when more palatable food is available. Livestock grazing is used for weed and brush control during stand establishment of Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine, and other conifers in Oregon, Washington, and British Columbia (Doescher, Tesch, and Alejandro-Castro, 1987), and of eucalypts in Brazil (Couto *et al*., 1994).

Nitrogen-Fixing Pasture Trees

The use of leguminous trees in pastures to improve grass productivity and provide extra fodder is very much a tropical phenomenon. The use of these trees is particularly common throughout Latin America, both

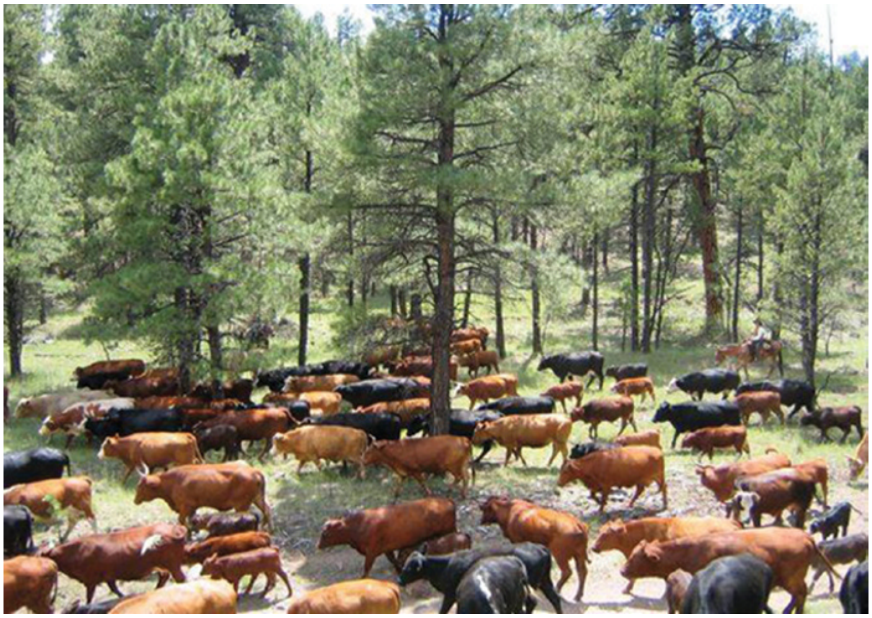


Figure 31.3 Grazing is being used to free ponderosa pine regeneration from competing weeds and brush in the Cascade Mountains of southern Oregon. Cattle must be moved frequently to avoid overgrazing and seedling damage. The stand is nearing the end of the stage in which sufficient forage is produced to support grazing. *Source:* S. D. Tesch.

in wet and dry tropical forest regions. The advantages of using leguminous trees in pastures are numerous. They are long lived, require low maintenance, provide high-quality fodder, fix nitrogen and stabilize soils because of their deeper rooting, and provide a source of fuelwood and timber (Topps, 1992; Mathison, 1994; Murgueito *et al*., 2011). The largest advantage is the effect that pasture trees have on nitrogen and organic matter, demonstrating increases in soil carbon content and grass productivity (Danso, Bowen, and Sanginga, 1992; Giller and Cadisch, 1995; Rhoades, Eckert, and Coleman, 1998).

The fodder quality for tree legumes varies greatly, but the species that are widely utilized because of their high nutrition and nitrogen contents are *Leucaena leucocephala* throughout the Neotropics and Australia (Mathison, 1994), *Albizia lebbek*, *Enterolobium cyclocarpum*, and *Samanea saman*, all tree species widely kept in pastures throughout Central America (Cajas-Giron and Sinclair, 2001; Griscom and Ashton, 2011); *Faidherbia albida* in the Sahelian region of Africa, and *Prosopis chilensis* in the temperate savanna woodlands of Chile, Argentina, and southern Brazil (Mathison, 1994).

In both Queensland, Australia, and in Colombia, South America, studies have shown even greater increases in livestock weight gain and milk production when the legume *Leucaena leucocephala* is planted in mixture with grass and grazed together. In Australia, the *Leucaena* is sown in wide-spaced rows with the grass, while in Colombia, it is sown as an intimate mixture (Mathison, 1994). Other potential candidates that are being tested using the same protocols, are the legumes *Calliandra calothyrsus*, *Albizia chinensis*, *Cajanus cajan*, *Gliricidia sepium*, and *Sesbania sesban* (Mathison, 1994).

Shelterbelts and Contour Hedgerows

Some complementary agri-silvicultural practices are designed especially for the purpose of soil conservation, particularly in semiarid regions of the world, where wind erosion commonly accompanies farming. The planting of **shelterbelts** is an effective means of reducing such problems; rows of trees are established upwind of agricultural fields to reduce wind velocity and thus lower the potential for transport of soil particles. Wind reduction also decreases water loss from leaf and soil surfaces, which increases crop productivity. Shelterbelts are also used to protect livestock from temperature extremes caused by either hot or cold winds. The use of shelterbelts to stabilize desertification processes in arable fields within the Sahel region of Africa, and in the central semiarid region of India, was considered a widespread success in the 1980–1990s (Shankarnarayan, Harsh, and Kathju, 1987). The tree used widely in the Sahel was the multipurpose neem tree (*Azadirachta indica*) (Deans and Munro, 2004; Atangana *et al*., 2014).

The beneficial effect of shelterbelts extends about 10–20 times tree height to the leeward side. The best structure is to have tall trees with a continuous vertical canopy. It helps to plant two or more rows of a mixture of tree and shrub species to create a stratified structure with the desired wall-like canopy structure. A single row of trees works poorly because gaps generally develop through which wind is channeled at high velocity. Sophisticated shelterbelt planting has been developed with radiata pine, where trees are pruned for timber production, but their arrangement in linear stepped age classes provides differential heights and therefore, structural thermal cover for livestock in adjacent fields (Hawke *et al*., 1997).

Shelterbelts were established on a large scale in the prairie regions of North America beginning in 1935, after the severe wind erosion that resulted from the droughts of the early 1930s (Bandolin and Fisher, 1991; Bird, 1998), and similar large-scale projects were carried out in China in the 1970s (YungYing *et al*., 1997). Species used for shelterbelts often include drought-resistant trees and shrubs with a wide range of size at maturity, many of which are rarely used in silviculture. Species used in North America include hackberry, autumn-olive, green ash, poplars, boxelder, and eastern redcedar.

On moderate to steep slopes in wetter climates, excess runoff is the major cause of erosion on agricultural fields. Rows of trees or shrubs planted as **contour** or **barrier hedgerows** can serve much the same function as the filter strips that are retained along water bodies during silvicultural operations (see Chapter 23). Hedgerows are established at intervals along the contours of a slope, with crops being grown in the spaces between. This practice can also function as alley cropping, if the pruned branches are used as mulch for the crops, but it can also be used solely for stabilizing soil. These are so effective that they can replace the need for constructing terraces on moderately sloping land.

Selection of Tree Species for Agroforestry

Species used for silviculture are not necessarily the logical choice for agroforestry because trees play different roles in the two systems. Ideal species for many agroforestry practices are those that can serve the protective function of preventing nutrient leaching or soil loss and at the same time provide a useful product of subsistence or commercial value. Species with these characteristics are called **multipurpose tree species** (see Table 16.4 in Chapter 16 on plantations).

Multipurpose trees can be most useful for improved fallows, alley cropping, contour hedgerows, and shelterbelts. The protective function is of greatest importance, but production of food or medicine, livestock fodder, wood suitable for burning or charcoal production, or poles or sawtimber at least partly compensates for the loss of cropland to the trees. These species can be used in most other agroforestry practices as well.

The concept of multipurpose trees has focused attention on lesser-known trees that are not used for timber purposes. Much work has been done to identify appropriate species and provenances with desired characteristics (Gupta, 1993; Burley and von Carlowitz, 1984). Legumes, alders, and casuarinas are highly desired for their nutrient contributions from symbiotic nitrogen fixation. However, different characteristics are required for use in different systems. For example, trees with rapid root growth are valuable for use in improved fallows, but they are likely to cause too much competition if used for hedgerows in alley cropping.

Efforts are being made to improve some tree species for use in agroforestry by controlled breeding. This task is made difficult because of the multiple functions desired of the species. In forest tree breeding, it has been found that concentrating on improvement of only a small number of characteristics gives the greatest gains. Improvement work has progressed the furthest with species and hybrids of *Leucaena*.

Some concern has been voiced that efforts to genetically improve multipurpose agroforestry trees will result in the use of a few superior species as exotics throughout the tropics and subtropics, just as has been done in tropical timber plantations. As with silviculture, it is often better to use a wide diversity of native species adapted to local climates and site conditions. Promotion of exotic tree species in agroforestry may bring about the loss of local varieties similar to the loss of local food crops that occurred when improved crop varieties were distributed (Hughes, 1994). Other concerns are similar to those associated with the use of exotics in silviculture, that large areas may be affected by a disease or insect problem, or that some introduced species may invade native vegetation or farmland, and become difficult to control.

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32

Application of Silviculture to Urban Ecosystems and the Urban–Rural Interface

Introduction

Urban and suburban environments and the role that trees and forests play in them can be considered one of the central pillars of current forestry. More foresters are now employed in managing the greenspace of cities and towns than at any time previously. The values of these trees are considered irreplaceable in resource issues dealing with urban climate mitigation, human health, open-space aesthetics, and human well-being (Pickett *et al.*, 2001). Since the 1980s, numerous studies have demonstrated the benefits of trees in urban and suburban landscapes, starting with a study by McPherson *et al.* (1997) that quantified the social and economic values of Chicago's forest in sequestering air pollutants, storing and sequestering carbon, and saving building energy use, both in heating during the winter and cooling in the summer. This was followed up with a modeling study on the benefits of trees in urban cities across the US in sequestering air pollutants (Nowak and Crane, 2002). These studies demonstrate that the net present value of the benefits of planting trees is nearly twice that of the estimated costs. More recently, studies have demonstrated the importance of the aesthetics of greenspace and trees in raising property values (Anderson and Cordell, 1988; Thompson *et al.*, 1999; Laverne and Winson-Geideman, 2003; Veseley, 2007), decreasing crime (Wolf, 2010), and the role that trees and vegetation play in increasing interception and soil infiltration that in turn reduce storm water runoff (McPherson *et al.*, 1999) and trap water-borne pollutants (Wang, Eckelman, and Zimmerman, 2013). Such reductions reduce the economic and environmental costs of running sewer systems and polluting water bodies downstream.

Urban forestry is now a rapidly growing field with its own sub-profession within forestry. The principles of forestry are the same, but it is important to realize that the built component of an urban environment is more dominant than the living plant component. Cadenasso and Pickett (2008) state that cities in and of themselves should be thought of in totality as ecosystems that are spatially heterogeneous in both living and built environments, and that these environments change over time. These principles are the same as those of a completely forested ecosystem. However, they state two more ecological process-based principles: human and natural processes strongly interact with each other, and ecological processes remain important factors in defining a city's environment (Cadenasso and Picket, 2008). Both of these factors are important in forested ecosystems, with perhaps the human element being less defining than in cities, but ecological processes overall being far more dominant as driving factors that influence forests as compared to cities. These principles are used as underlying drivers to manage an urban forest for different social values. In this chapter, three important categories of social values will be defined: (1) aesthetics and landscape design; (2) the role of trees in mitigating urban climate extremes, air pollutants, and energy loss from buildings; and (3) the role of vegetation in mitigating stormwater runoff.

Aesthetics and Landscape Design of Urban Forests

When considering an urban landscape, designs need to recognize that there is always a current landscape upon which to work and transform. Just as with forests that are managed for timber or wildlife, nothing begins in a vacuum. There is always a legacy of history that must be accommodated. Designing an aesthetic park, street, or path requires careful planning that can envision the future stand structures and spaces that will be occupied many years after planting. Such designs must retain an inherent flexibility to accommodate the values of urban societies that are constantly changing and creating new demands on greenspace.

Urban Forest Categories

Urban forests can be categorized into three kinds of landscapes and habitats: (1) large forests and woodlands, (2) avenues, streets, and walkways, and (3) courtyards

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and squares. Large forests and woodlands can include hundreds to thousands of acres (hectares) and can be very important central or peripheral components of a city's or town's planning for open space. Many European cities have large forests that encircle their centers (e.g., Paris, Moscow, London) primarily because they were often originally the hunting grounds of royalty (barons, dukes, and kings). The centers of most European towns were fortified, confining buildings into tight spaces with narrow streets with no room for greenspace. This is still very apparent, compared to even the oldest North American cities that often have an extensive forest at the heart of the city. Some cities had the opportunity for thoughtful planning by landscape architects such as Frederick Law Olmsted and his disciples (e.g., Central Park in New York City; The Emerald Necklace in Boston). Almost all of these forests are semi-natural, and some cities have actually retained old-growth forests in their centers (e.g., Vancouver, British Columbia; Panama City, Panama).

Streets, avenues, and walkways comprise the second category. Because they are usually linear and directed, and serve the main function of moving with or without motorized transport, arrangements of trees also tend to be linear and more formal. Some cities are well known for their extra-wide boulevards (e.g., Paris, Washington D.C.) or for their trees (e.g., London, England, the London plane tree). In European cities, many of the wider ring roads, greenways, and boulevards are immediately adjacent and on the outside of the old city walls.

The third and last category includes small parks, squares, and courtyards. In this category, most designs are formal and open. Together, different cultures have used urban forests for different social values and uses. For example, Mediterranean cultures have traditionally used forests and parks as places to picnic and to recreate in social groups. In the hot climates of the Mediterranean, trees and woodlands serve to provide shade and open space to do this. Northern forest cultures (e.g., Scandinavia, Germany) use forests much more extensively for snow sports (cross-country skiing) and summer sports (running, hiking) and for gathering berries and mushrooms.

Principles of Design

Whenever open-space and landscape design is to be considered, there are four ecosystem attributes that must always be included: **social**, **experiential**, **functional**, and **ecological** (Bell *et al.*, 2005) (Fig. 32.1). Social aspects of design for parks, courtyards, woodlands, and forests need to be considered for the use of vegetation to contrast with the built environment, its noise, activity, and bustle. Many people consider greenspace to allow an escape to solitude and communing with nature.

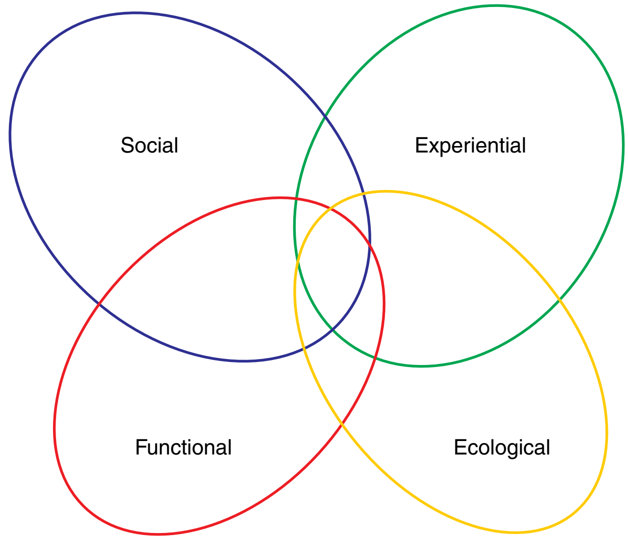


Figure 32.1 A Venn diagram depicting the attributes that must always be considered in urban forest landscape design. *Source:* Mark S. Ashton.

Others want greenspace as a place to meet, to talk, and to recreate (e.g., playgrounds, ballfields), and still others as a place to exercise. Thus, social activities are different, and in many cases are incompatible with one another. Planning is needed for zoning and identifying separate uses within the space, or deliberately allocating space to a predominant use.

There are strong cultural differences in the way urban forests and parks are perceived. Northern Europeans are very comfortable with forests and a feeling of remoteness. Surveys show that they like passive individual exercises, such as hiking, running, snow-shoeing, or skiing. Many Latin and Asian cultures prefer more open woodlands, where visibility is greater and there is a stronger feeling of security. This means that understanding the cultures of society in urban forestry is an essential element of planning and developing silvicultural prescriptions. In North America, most urban environments are now multicultural, which make planning and accommodating society's diverse values all the more difficult.

All open greenspaces, and especially forests, provide a strong experiential contrast in aesthetics, noise, and feelings, as compared to the usual urban environment of people, cement, and traffic. The senses are immediately exposed to greenery, flowers, birds, quiet, and the smell of grass and leaves. Exposure to nature has been shown to be critical to human development and psychological health (Taylor, Kuo and Sullivan, 2001; Taylor and Kuo, 2006).

Functional attributes that need to be considered when planning and designing for forests and parks include two main considerations: (1) access, and (2) security and

safety. Different spaces demand different kinds of access by vehicle, bike, or foot path. Spaces need to be designed for different users and cultures that include sports fields, hiking trails, barbecue areas, meeting areas, and places of solitude. Also, paths and trails need to be designed to wind in ways to promote a feeling of seclusion and remoteness in certain areas, and to be straight in other areas to promote visibility and a feeling of security. The number of users may be the same in a landscape that is open with straight paths, but the visibility makes those users appear more numerous than if paths were winding and secluded. The experiential feeling of the users in each circumstance is very different.

Climate also dictates functional attributes. In colder climates, planning and design tend to be around activities (hiking, bicycling) as compared to hotter climates where shade and more passive use of the forest and park space are desired, such as the lawn bowling games played throughout southern Europe. The last attribute is the ecology of forest and park design. Connectivity between parks and forests is the most important ecological consideration. The greenways of streets and boulevards and the riparian zones of waterways and wetlands should be used as the connections between larger greenspaces that comprise courtyards, parks, and forests.

Components of Design

There are three *primary components* to using trees and vegetation in designing streets, courtyards, and parks. These are: **edges**, **vistas**, and **features**. All complement one another. Trees and shrubs that are used as edges are also used to soften hard lines of the built environment, such as walls. Edges can also be used to accent or provide a background to buildings, or to hide or screen an area. Finally, edges can be used to unify different stands and building structures. Vistas are designed to create the viewshed, and the vista itself is created by edge. Thus, there are two components of design that are equal and opposite to each other. Two kinds of vistas can be created through the use of edges: those that draw only the eye to a viewshed, and those that actually draw the body either by walking along a trail or driving along a road. The edges on either side of a vista are the structures that promote drawing the eye toward the opening. Roads with avenues of large symmetrical rows of trees can be very effective in creating an experiential environment to the user that wills the traveler to move through the avenue. The last component to consider is the use of features within landscapes. Features include the built structures, such as statues, temples, and shrines, as well as natural structures, such as snags, cavities, and old trees. Again, features do not exist in a vacuum but depend upon vistas that highlight and draw the eye and the body toward the feature.

These three primary components of vegetation design should be used together. Edges are used to provide intimacy and secrecy in an environment. For example, a small park in the middle of a busy street square can create silence and quiet by enclosing the periphery with multi-layered evergreen foliage that has a strong visual buffer. Vistas can be used within winding paths with strong edge that draw the body forward from an enclosed space to an open space. Taking full advantage of topographic relief can provide vistas with strong depth. Also, taking advantage of vistas with features such as a large tree or a shrine within the middle of a forest opening amplifies the experience (Fig. 32.2).

Three *secondary components* for using trees and vegetation in landscape design are more ephemeral, in the sense that if they are there, they can be used, but in many cases, these attributes are not there. They include the use of **light**, **color**, and **texture**. Light can be an intoxicating experiential phenomenon when sunflecks and the contrast between shade and the dark foliage is set against the heterogeneity of sunlight streaming through a forest canopy. This can be amplified by structuring and stratifying the stand with forest openings, but it is only effective on sunny days. Seasonality and the nature of climate play an important role in deciding whether to amplify these effects within a forest. Color, like light, is ephemeral and again strongly tied to seasonality (e.g., spring flowering, fall foliage, the onset of early flush with the rains). Understanding the nature of tree and forest composition allows the forester to amplify these effects by selecting trees and shrubs along edges and/or features that create the color at certain times of the year. The last secondary component is texture, another characteristic that can be ephemeral and is also in the eye of the beholder. For example, design can draw out and highlight the foliage textures of mosses and understory ferns and of rock erosion and rock arrangements.

Putting Designs Together

These three primary and three secondary components of arranging and managing vegetation should always be used to accommodate the four design principles that must be considered (social, functional, experiential, and ecological). With this in mind, there is one other overarching consideration that can be described as **harmony**. If streets and structures are formal and symmetrical, it is best to arrange the vegetation in the same way. Similarly, if the landscape has an irregular naturalistic look and feel, then the theme of vegetation design should be informal, non-symmetrical, with rounded and varying edges (Box 32.1).

Figure 32.2 A collage of photographs depicting the use of vegetation to: **(a)** create edge to screen suburbs at World's End, Boston, US; **(b)** provide edge to soften a wall at Hidcote Manor, UK; **(c, d)** provide edge that guides both eyes and person through use of vistas at the Arnold Arboretum, Boston, US; **(e)** create features out of whitebark pine, Mount Hood, Oregon, US; **(f)** highlight a stone bridge as a feature, western Scotland; and **(g)** highlight a pond as a feature, Stowe, UK. *Source:* **(a–g)** Mark S. Ashton.

Box 32.1 "Naturalistic" designs and silvicultural prescriptions based on stand dynamics and silviculture can accommodate a more diverse set of ecosystem services using trees and vegetation rather than traditional landscape designs. Examples are provided for an urban woodland park and an urban walkway.

Restoring an Urban Woodland Park

Objective

Creating greater vegetation diversity for wildlife habitat, greater structure for mitigating stormwater runoff, reducing costs of maintenance, and improving soil fertility.

Current and Historical Condition

Figure 1 illustrates the existing open woodland on the Yale University Campus in New Haven. The woodland is growing in a well-drained glacial till on a sandstone ridge surrounded by university buildings. Most of the site drains to the east and west off the ridge and down to the south with a hot and sunny southerly exposure. There are more mesic areas at the toe of the ridge to the SE and SW. Only a few relic open-branched oaks of the original woodland remain. The southern exposure and the dry sandy soils make it originally an oak–hickory site with an open sedge and vaccinium (blueberry) understory. However, at the toe slopes, the woodland would have become more stratified and closed with sugar maple forming the canopy and understory trees of dogwood, sassafrass, hophornbeam, and shrubs of witch-hazel. Only a few sugar maple survive. On the mesic toeslopes, ephemeral herbs, such as star flower, wild sarsparilla, and Canada mayflower, would have dominated the groundstory.

The current condition of mowing, leaf raking, and fertilization of the lawn, with heavy foot traffic, has led to soil degradation, compaction, erosion, and high surface runoff. There are no age classes of trees that have been planted to succeed the older age class that has high amounts of dieback. The current design is a very traditional, open and barren one with little planning for ensuring a balanced age class of future mature canopy trees and no educational value.

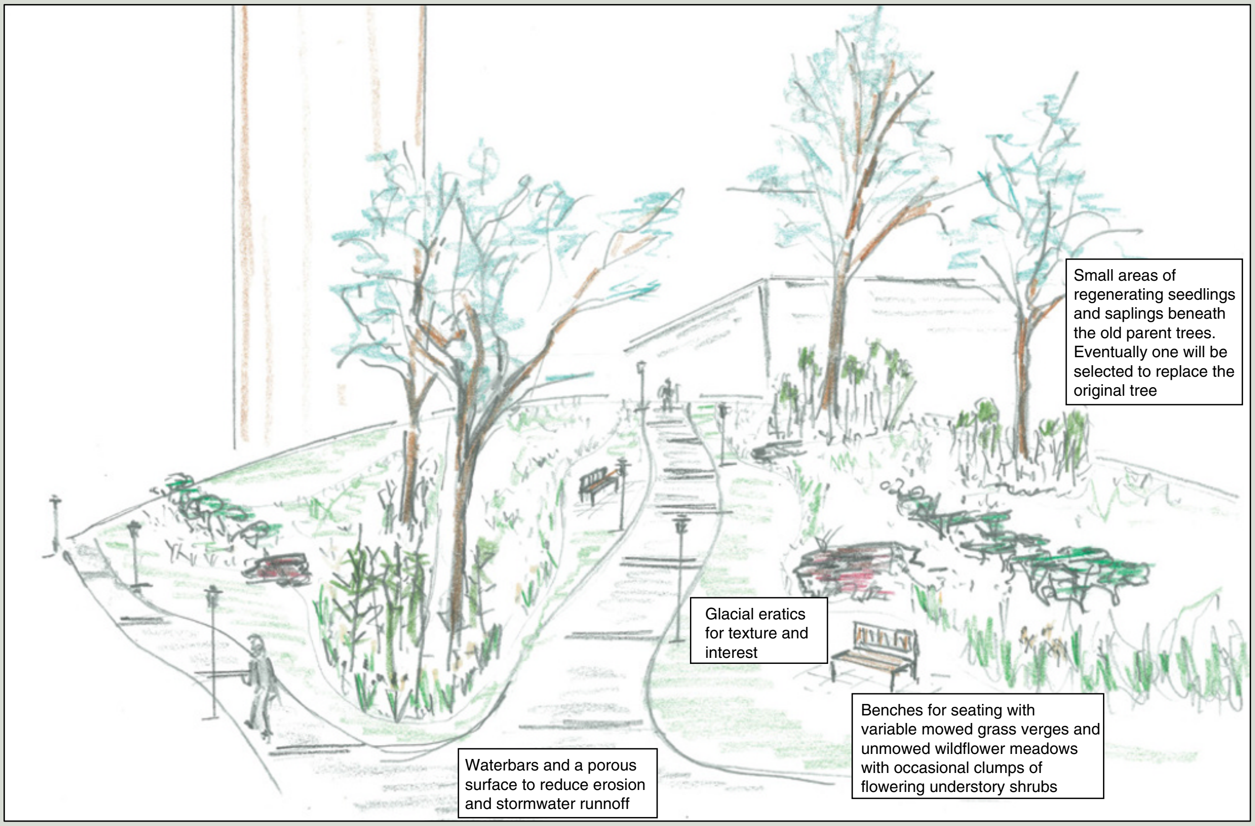
Silvicultural Prescription for Future Condition

Figure 2 illustrates a prescription for the same site with the objective of restoring the woodland. Methods of doing this rely chiefly upon use of low-cost natural regeneration using the seed-tree method. Patches around the existing oak and hickory trees are demarcated and protected from mowing and leaf raking to facilitate seedling establishment. To create multiple balanced age classes (as in a selection system) seed trees and their associated patches can be established at 10-year intervals. Each patch will gradually select down through release treatments to one or two trees that attain the canopy to replace the old original seed tree and thus start the regeneration cycle again. No planting is necessary.

Exotic plantings (and sculptures) can be removed, and supplemental understory native tree plantings (e.g., dogwood, carpinus, witch-hazel) can be implemented particularly on the more mesic lower slopes. The remaining area not demarcated to patch regeneration will be encouraged to grow back to sedge and vaccinium with more occasional

Box 32.1 Figure 1 A very traditional open woodland park in the middle of the Science Hill area of Yale University in New Haven, CT. The photograph was taken northwards showing the southern slope exposure to the south. *Source:* Mark S. Ashton.

Box 32.1 (Continued)



Box 32.1 Figure 2 A graphical illustration of the same slope and aspect depicted in the photograph in Figure 1, but with the implemented silvicultural prescription for restoration. *Source:* Mark S. Ashton.

kalmia. This can be done through plantings and direct seeding of tilled areas. More open areas at the bottom and tops of the slope can be designed for variable mowing regimes that encourage wildflower meadows. This can be started by scarifying the soil and direct seeding in the spring when soil moisture is high. A mixture for southern New England includes native grasses, sedges, and wildflowers that can be timed to sequentially flower through the growing season (e.g., lysimachia, black-eyed susan, coreopsis, solidago, asters). Within the meadows, more frequently mown open spaces can be created to provide both seclusion and viewsheds to encourage people to meet, to stay, and to find solitude. A larger open area for passive recreation can be created toward the crest of the slope.

The main walkway to the summit should be designed such that it is a pleasurable walk through a regenerating woodland. This could include careful placement of features such as erratics and glacial rocks depicting the original geology (that was formerly removed) and that encourage establishment of mosses and ferns comprising textures and color that attract and draw the eye along the walk. The central walkway should also be the core viewshed that can provide the walker a feeling of openness and closure in different places and that can promote people to stop and sit. Trail design should promote infiltration, and divert any surface runoff through waterbars and use of gravel. Lighting and carefully sited benches ensure comfort and a feeling of security.

Benefits of the New Prescription

An attempt to increase and then maintain a range of species compositions, age classes, and habitats, promotes a greater resiliency to unpredictable insects, disease, and climatic disturbances. The habitat diversity and the features and vistas within them (e.g., rocks, big trees, glades, and openings) that are designed along trails create points of interest, feelings of both secrecy and openness. The clumps of trees and shrubs break up visibility providing a greater sense of mystery. The overall design connects the park to the original ecology and geology of the site and its land use history.

(*Continued*)

Box 32.1 (Continued)

Redesigning an Urban Walkway

Objective

Creating greater vegetation diversity to provide greater shade, tranquility, and aesthetic, and to reduce glare from the adjacent street, mitigating stormwater runoff, and sequestering pollutants.

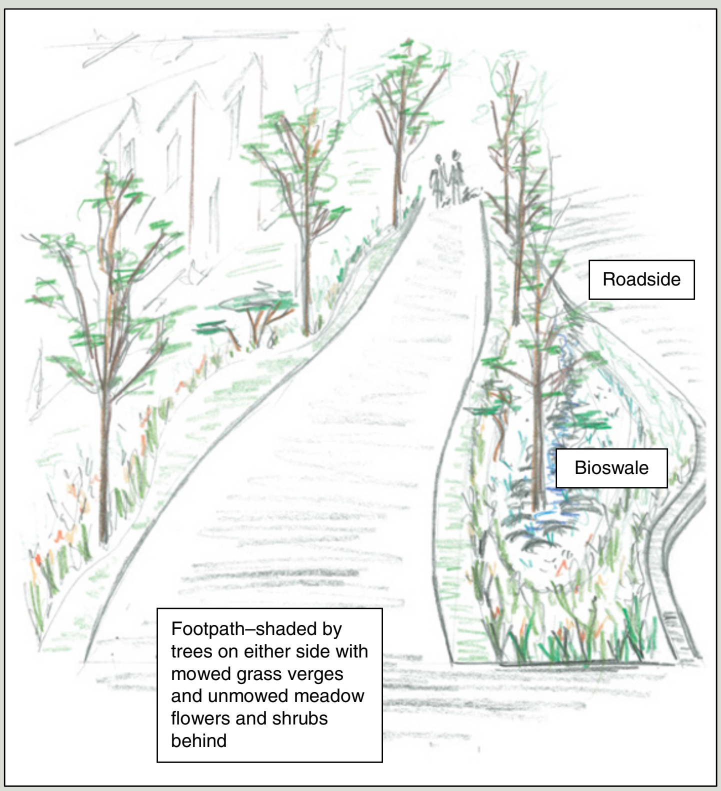
Current and Historical Condition

The site is a traditional linear street in New Haven, Connecticut with a north–south orientation with about a 10% slope (Figure 3). Street parking, the road itself, and cement walkways on either side with little space for unpaved surface area have promoted excessive stormwater runoff that erodes the edges of unpaved areas and increases siltation downstream. The original street was cobblestone and served as the main conduit to a series of mansions arranged on either side that were the houses of wealthy industrialists during the 19th century. The original street trees were sugar maple and pin oak that mostly died from road salt and injuries sustained from vehicles. The street was replanted recently with ball-and-burlap scarlet oak with a caliper of about 2 in (5 cm) DBH.

Silvicultural Prescription for Future Conditions

Figure 4 illustrates a prescription for the same street with the objective of creating a greater functional capacity to mitigate stormwater runoff and to sequester pollutants and

Box 32.1 Figure 3 Prospect St, New Haven, Connecticut. A traditional street that could reflect any street in a city. *Source:* Mark S. Ashton.



Box 32.1 Figure 4 A graphical illustration of the same street from the same direction depicted in the photograph in Figure 3. To the right is a bioswale that takes the surface runoff from the street. It occupies several former parking spaces. To the left is the curvilinear walkway shifted slightly over toward the house side of the street verge to provide extra space for a vegetation buffer between the walkway and the street. *Source:* Mark S. Ashton.

Box 32.1 (Continued)

particulates, while at the same time improving the experience of walkers by providing shade and a greater diversity of vegetation structure and composition to partially hide the street and to ensure no runoff from the walkway.

The walkway can be placed further back from the street and, though linear, can be made to appear non-linear by curves that give the illusion of greater variability even though it is as direct in distance. The stormwater off the street can be diverted into bioswales at intervals down the slope. The swales are arranged to cut into the parking areas at intervals that sacrifice parking spaces in return for greater vegetation structure and greenery for walkers. The existing scarlet oak street trees can be left in place to grow up to create a uniform shaded canopy for walkers and drivers, reducing glare, increasing interception and promoting shade especially in the summer heat.

Benefits of the New Prescription

The new design dramatically reduces stormwater runoff and sediment loading to the sewer system; sequesters particulates, heavy metal, and petroleum pollutants that are washed from the road surface; provides a more comfortable walking and driving experience by reducing glare and temperatures on hot and sunny days; and gives walkers a more aesthetic appeal and experience by using the vegetation as a buffer to road traffic.

Mitigating Urban Meso- and Micro-Environments

If cities and their urban environments did not have trees and woodlands, it would be hard to imagine what their climates would be like. There is now such a large body of information demonstrating the net benefits of tree cover, current city planners and urban foresters need to systematically maximize this for potential benefit. Unfortunately, and all too often, park budgets are the last to be funded in cities. Utilities managers think that powerlines and power infrastructure should take precedence over forests and street trees, and transport departments see trees and forests as impediments, and places for expansion and road widening, rather than as a complementary benefit. Some forward-thinking transport departments focus on the traffic-calming benefits of trees, and follow "Complete Streets" plans which integrate multiple transport types (bikes, cars, and pedestrian safety). However, most transport departments are not so sophisticated, despite study after study demonstrating the importance of tree cover in reducing glare, decreasing noise (Anderson, Mulligan and Goodman, 1984), moderating climate by shading at both micro- and meso-scales (Akbari *et al*., 1992; Heisler *et al*., 1995; Shashua-Bar, Pearlmutter, and Erell, 2009), sequestering carbon and air pollutants (McPherson *et al*., 1997; Nowak and Crane, 2002), conserving energy within buildings (Heisler, 1986; McPherson, 1987; Heisler, 1990; McPherson and Rowntree, 1993), and reducing storm water runoff.

Transport: Streets and Highways

Glare

One of the most tiring aspects of driving is when the sun is either directly in the eyes of a driver, or reflected from adjacent surface bodies (e.g., snow) into the driver's eyes (Fig. 32.3). There are many ways of moderating and eliminating glare along roadways, streets, and walking paths, that all involve the use of vegetation aligned in a way that reduces both direct and indirect glare when the sun is low in the sky, primarily on eastern and western sides of roads.

Noise

The vegetation, and especially woody vegetation, can act to reduce noise effectively. The density of the foliage, the thickness of the vegetation buffer, the height, and the seasonality of the foliage (evergreen, deciduous) all influence the effectiveness of noise reduction by both scattering and absorbing it from highway traffic. For most effective noise reduction, trees should be planted: (1) as close as possible to the source of the noise, (2) in dense plantings or maintained as early stem exclusion if originating from natural regeneration, 100 ft (30 m) wide or greater, (3) evergreen species, and (4) well stratified to ensure an even distribution of foliage and wood (McPherson and Rowntree, 1993). Under these circumstances, the noise reduction can be as much as 75% and usually over 50% (Cook, 1978). Narrow dense belts of evergreen vegetation of single rows (e.g. cedar, juniper) can effectively reduce noise by at least 25% when roadside space is limited (Reethof and McDaniel, 1978). Evergreens may be good as roadside plantings but are rarely planted as a street tree because they block sight lines when pulling into or out of driveways

Vegetation, and wood in particular, can be even more effective in moderating sound from roadways when it is arranged within topography where the roads are sunken or the embankments are raised so that soils absorb sound as well. In these circumstances, up to 90% of the sound can be reduced such that sometimes you can walk up to the edge of a major highway without knowing it, because its noise-reduction vegetation and landscape plan have been so well designed. Noise-reduction studies have been carried out under different vegetation and landscape

Figure 32.3 Roadside beech trees shade the road by reducing the direct glare from the sun and by minimizing indirect glare from surface reflection off the road or ground (snow) surface. *Source:* Mark S. Ashton.

designs. Many of these studies were done when the interstate highway system was being constructed in the US.

- Eyring (1946): higher frequencies are more attenable than lower frequencies.
- Cooke and Van Haverbeke (1971): suggested plantings should be at least 30–50 ft (9–15 m) high and 100 ft (30 m) in depth to provide traffic noise abatement.
- Whitcombe and Stowers (1973): broadleaf evergreen hedge was most efficient and the leaf characteristics were more important than the depth of the planting.
- Van Haverbeke and Cook (1974): tree-covered earth mounds are more effective than earth mounds alone.
- Huddart (1990): low frequencies are absorbed by porous soft ground (grasses and forbs); high frequencies are absorbed by leaves and trunks of trees. The effectiveness of vegetation is greatest closest to the road. Highest attenuation was with dense interlocking spruce plantations.

Trees and the Urban Climate

Micro- and Meso-Climate

Tree cover varies from individual shade trees to forests and parks within cities. This range in tree canopy cover influences local (micro-scale) and regional (meso-scale) effects of heat exchange among urban surfaces. Trees do this by moderating wind speeds and changing wind direction, shading surfaces of the built environment (pavement, grass, roofs), and by increasing transpiration of water back into the atmosphere, thus cooling it. This is not necessarily as simple as stated here. Usually there are strong benefits from one attribute (e.g., shading) that outweigh the costs of other negative attributes (e.g., reducing wind speed and therefore heat dissipation). Overall, many studies have demonstrated that tree cover for the urban climate environment has a net benefit in most circumstances (Heisler *et al*., 1995). In a temperate climate trees within cities can: (1) reduce direct solar radiation at the ground surface by up to 90%, (2) reduce wind speeds over 60%, and (3) by transpiring water vapor into the canopy air, cool the surroundings (Heisler, 1986, 1990). With proper planning, these influences taken together can lower ground-surface temperatures beneath tree canopies by up to 9 °F (5 °C) (Akbari *et al*., 1992). This is obviously most effective in the summer but in the winter trees need to perform the opposite function of allowing direct radiation to increase temperatures. Deciduous trees allow for this and can also function to reduce wind speed that promotes temperatures to build up rather than be dissipated away by colder air.

Forests and tree cover are most important where cities are in climates that are arid and hot. The tree cover can moderate surface temperatures for the city meso-environment in general and provide shade and lower temperatures below the canopy of the micro-environment at the scale of a shaded street or a shaded bench within a park. The outdoor cooling effect is not just related to the tree cover and shade but to the transpiration of vegetation in general. For example, in an arid environment, courtyards with shade trees and grass reduce air temperatures on average by 4.5 °F (2.5 °C), and considerably more under the shade of the actual tree, while in the open, temperatures averaged 93 °F (34 °C) (Shashua-Bar, Pearlmutter, and Erell, 2009). In these same conditions, water use of the grass was halved with the use of shade trees. At larger scales, urban environments with tree cover have been shown to moderate the hot summer and cold winter temperatures associated with the regional heat island effects of a large built landscape, such as the

megalopolis between Boston and Washington DC (Rizwan, Dennis, and Chunho, 2008; Mackey, Lee, and Smith, 2012). In forested cities, temperatures can be reduced by as much as 5 °F (3 °C) in the summer as compared to cities with little to no tree cover.

Pollutant Sequestration

It is amazing to think that forests and trees within urban environments may be of most value in relation to human health. It does not seem the most logical and obvious linkage, but studies as early as the classic research conducted in the 1970s by Smith (1990) demonstrated the trapping and sequestration potential of air pollutants by tree foliage. The Smith study showed the role that foliage plays in trapping particulates and soot that contain heavy metals from the exhausts of cars. A more recent modeling study by Nowak, Crane, and Stevens (2006) suggests that annual urban air pollution [ozone (O_3, PM_{10}), nitrous dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO)] removal in the US can be up to 711,000 metric tons, with an estimated $3.8 billion value. They suggest that maintaining and increasing a healthy forest cover should be one important strategy utilized for increasing human health. In several studies, one of the major pollutants, ozone, has been demonstrated to be reduced with tree cover (Cardelino and Chameides, 1990; Nowak *et al.*, 2000). These studies and others have allowed the US Environmental Protection Agency (EPA) to develop guidelines for increasing tree cover in cities to improve air quality and to meet EPA air-quality standards (US EPA, 2004).

Finally, carbon storage and sequestration in urban environments, though not as high as a fully closed forest, can also have significant values. Nowak and Crane (2002) estimate that based on tree inventory measurements from 10 cities in the US, about 22.8 million tons of carbon per year is sequestered and about 700 million tons of carbon is stored.

Energy Conservation in the Built Environment

Shelterbelts and Conserving Energy Lost Through Convection

Shelterbelts are usually associated with agroforestry systems and serve to moderate winds and temperatures to increase crop yields in arid environments or to provide shelter to livestock in hot or cold climates (see Chapter 31). However, shelterbelts can just as easily be used in urban environments to moderate winds and reduce energy lost from convectional losses from buildings. Different densities and heights of shelterbelts influence winds in different ways on the leeward side. Shelterbelt canopies that are not dense do not reduce wind speeds as much as dense canopies, but their effects in reducing wind speed have greater effects further away from the the shelterbelt. Measures of reduced wind effects are measured in H units, which are distances away from the shelterbelt as measured by the height (H) of the shelterbelt (Fig. 32.4).

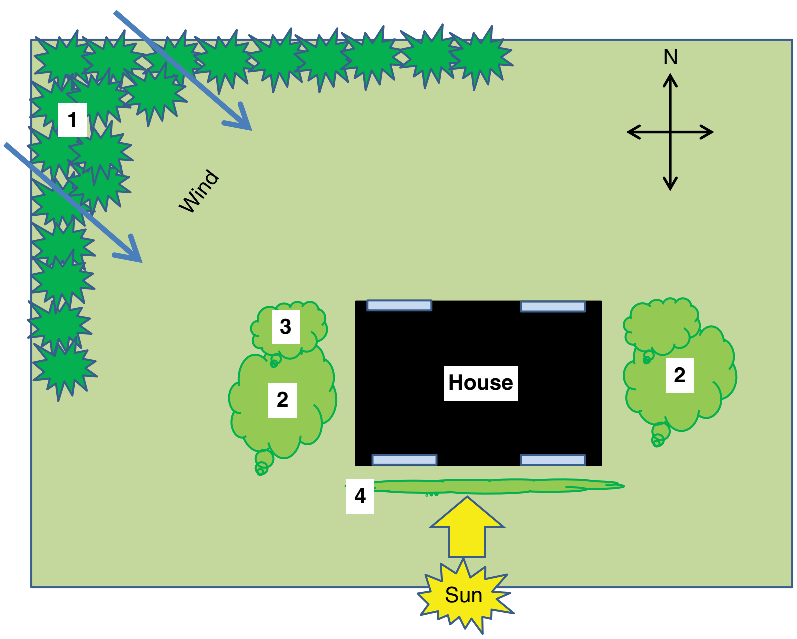


Figure 32.4 Tree arrangements to maximize energy conservation around a house at a northern latitude. Evergreen windbreaks (1) should be placed on the northwest corner of the garden to reduce winds from the northwest and therefore convectional heat loss in winter. Low evergreen hedges and vegetation below windows adjacent to the sides of the house to also reduce convectional energy losses (4). Canopy tree shade on eastern and western sides of house to reduce heat loading on the roof from summer sun (2, 3). Trees that are placed on the southern side should be deciduous with a tall bole with a high canopy to maximize shade in the summer when the sun is high in the sky, and to maximize direct sunlight in the winter when the sun is low and can come through windows. *Source:* Mark S. Ashton.

Conservation Through Radiant Energy

Just as the outside environment conserves energy, trees can be used to shade the roofs of buildings in order to influence the radiant energy entering the inside environment. In temperate climates, trees can be used for shading roofs in the summertime and not during the wintertime. In the wintertime, radiant energy conducted into the roof and through the windows should be maximized because of the cold outside. Deciduous trees with deep crowns that develop in summer (e.g., maples) are best for this purpose. Similarly in arid climates, evergreens can be utilized for year-round shade.

Proper tree placement around a house is critical to maximize energy conservation. For the summer, shade trees planted on the east and west sides of houses are best in temperate climates, due to the long east–west path the sun takes at that time of year. Trees planted on the southern side create more shade on a house in the winter which is when radiant energy from the sun into the house needs to be allowed (see Fig. 32.4). A variety of studies done in the 1980s, a time when rising fuel energy was a concern, demonstrated the most energy savings in the desert southwest by appropriately arranged shade trees that reduce the energy use of air conditioning up to 25%, while more moderate energy savings could be obtained in more northerly and temperate climates, up to 12% less energy use (Heisler, 1986; McPherson, 1987; Heisler, 1990). Still, in a study in Chicago, the planting of three trees per building lot on average would increase the tree cover by 10% and save the residents about 10% per house in energy costs.

The Application of Silviculture to Urban Watersheds

Baseline Studies in Urban Environments

The use of vegetation, and especially the use of trees and forests in urban environments, is perhaps the cornerstone of **green stormwater infrastructure** (GSI). It provides a set of natural resource techniques using soils and vegetation that substitute for the engineering and plumbing of urban environments to divert surface runoff from impervious pavement and roof tops and into sewer systems. Such engineered solutions prove to be very expensive, physically centralized, and more prone to risk of disaster. Many urban foresters are now charged with developing alternative techniques that are primarily a decentralized green network of constructed treatments designed to improve stormwater runoff quality, reduce stormwater runoff quantity, and reduce peak runoff, much like what forests do in their natural environment (Wang, Eckelman, and Zimmerman 2013). Green stormwater infrastructure comprises a range of approaches that include the use of vegetation. These include: **green roofs**, **bioswales**, **rain gardens**, and **enhanced tree pits**.

GSI trial treatments for the different approaches have shown promise, enough to merit implementation on a much larger scale. Many cities in the US have invested in both demonstration sites and in city-wide GSI implementation to comply with the Clean Water Act. Cities that have made considerable investments in GSI include: Kansas City, MO; Detroit, MI; Cleveland, OH; Chicago, IL; Seattle, WA; Portland, OR; New York, NY; and Philadelphia, PA (Box 32.2). All have invested billions of dollars to implement GSI in an effort to both reduce costs and attain compliance with the Clean Water Act.

The Science behind Green Stormwater Infrastructure

Green roofs come in all shapes and sizes. They can be considered a living vegetated water-retention system that also delays stormwater flow off the roof, much like the canopy interception and surface soil water storage within a forest. The infiltration and storage of the water within the green roof also serves to help filter and cool the building in summers while insulating it in the winter. Depending upon the strengths and load-bearing engineering of the roof, there are two kinds of green roofs: (1) shallow roofs that contain 2–4 in (5–10 cm) of soil and shallow-rooting plants such as succulents that can often be modular when laid down; and (2) deep roofs with 6–12 in (15–30 cm) of soil, more deeply rooted vegetation for greater plant diversity and structure with a larger capacity for stormwater retention. Green roofs have been shown to be effective at reducing both stormwater quantity and overall pollutant loading, with shallow green roofs having an average stormwater retention rate of 56% (Gregoire and Clausen, 2011), and deep roofs having an average of 69% (Mentens, Raes, and Hermy, 2005).

Bioswales comprise a variety of designs that are designed as an alternative to storing the water underground in a tank and allowing the water to partially infiltrate into the subsurface soil (Fig. 32.5). Bioswales and constructed wetlands are often linear, slightly sloping open channels that can have an underground perforated drainage pipe. Three kinds of swales can be defined: **dry swales** incorporate a conventional drainage system beneath, **grassed channels** resemble conventional drain ditches, and **wet swales** incorporate a mixture of vegetation, including trees and shrubs that are hardy in varying dry and inundated soils. The kinds of trees planted in these conditions are tolerant of pollution

Box 32.2 Green stormwater infrastructure programs of Portland, Oregon, and New York City.

New York City, New York

The New York City (NYC) urban area comprises about 115 square miles (300 km2) of which 60% is impervious surface (Nowak and Greenfield, 2012). In 2016 New York's population was estimated to be over 8.5 million people with a growth rate of over 4% since the 2010 Census (US Census, 2013). A combined sewer system (meaning both sewage and stormwater are combined in one piping system and treated), serves about 50% of the land area and 65% of the sewered area for NYC. During high rainfall storms, the stormwater is sent directtly to 400 combined sewer overflows (CSO). Approximately 27 billion gallons of untreated stormwater is delivered into NYC's waterways each year because of overflow issues (NYCDEP, 2013).

In 2008 the New York City Department of Environmental Protection (NYCDEP) published the New York City Sustainable Stormwater Management Plan as a part of the city's NYC Sustainability Strategic Plan. The plan provides a solution to meeting compliance regulations by a hybrid program that uses both green stormwater infrastucture (GSI) (bioswales, enhanced tree pits, porous pavement) and traditional engineered technologies such as sewer and plant upgrades. At the time of the 2008 analysis, 7% of the city's waterways were considered the most "impaired", meaning that they have very low rates of flow and constrained channel dimensions for their respective drainage area. The effort towards mitigating CSO events has been focused on those sewersheds associated with the most impaired waterways. This targeted approach to stormwater management sets NYC apart from other large cities (e.g. Philadelphia, Washington DC) that have adopted approaches to GSI that are much more evenly distributed throughout their watershed area as a stormwater solution (NYC, 2008; NYC, 2010).

The GSI program in NYC began with the construction of pilot projects with NYCDEP funding. Since 2010, millions of dollars has been spent on a green infrastructure that has funded construction, design, monitoring, and maintenance of green infrastructure source controls within the targeted impaired watersheds. The NYC approach focuses on the study and then incremental implementation of a set of standards for bioswales. As part of the 2011 Consent Order, NYCDEP committed to spending hundreds of millions of dollars to build, monitor, and maintain green infrastructure. During this first green infrastructure build-out phase (2010–2015), NYCDEP achieved the goal of capturing runoff from 1.5% of the impervious area citywide. By 2020, NYCDEP expects to control runoff from an additional 2.5% of impervious area. In each of the final two 5-year periods, 2025 and 2030, NYCDEP has a set a goal to capture rainfall from 3% of impervious area (NYCDEP, 2010); which in total would cover all of the most impaired waterways of the City.

Portland, Oregon

The City of Portland, Oregon is an urban area that, compared to many urban areas (e.g. Houston, Atlanta), benefits from comprehensive planning. To get its storm water permit, the Portland prepared a Storm Water Management Plan (SWMP) in compliance with the Federal regulations of the Clean Water Act. The SWMP describes best management practices (BMPs) that the city needs to implement to reduce pollutant discharge. Portland's stormwater management area comprises approximately 15,627 acres (6325 ha). Over one-third of Portland's 2500 miles (4000 km) of sewer pipes are over 80 years in age. Portland is using green infrastructure reduce the use of its old sewer system and to make it operate more efficiently by keeping stormwater out of sewers. Portland planners also recognize that green infrastructure brings greenery and nature into the city, providing numerous side benefits that include improving both mental and physical health, increasing property value, conserving energy, enhancing wildlife habitat, and saving money by avoiding or delaying the replacement and upgrade of the sewer pipe infrastructure. Planning is therefore used as a tool to integrate green infrastructure into everything from urban design, transportation, watershed health, and open space. It does this by a series of programs that comprise "green streets", eco-roofs, tree pits and bioswales. All these programs are intended to manage stormwater runoff and to protect water quality. A "green street" uses vegetated verges to manage stormwater runoff at its source, reducing flows and improving water quality. Streams, forests, and wetlands within Portland's urban parks and open spaces are also used manage stormwater naturally. As of 2016 there are over 1,500 green streets, tree-pit systems, and bioswales that were being used to manage stormwater surface runoff in the city.

and salt, and are capable of withstanding droughts and standing water. These are inherently trees and shrubs of floodplains. Bioswales have an important capacity to absorb and retain nutrients, depending upon the nature of the soil and vegetation. In addition, they can also dissipate the energy and control the incoming flow of stormwater. Bioswales are ideal for roads, parking areas, and trail systems.

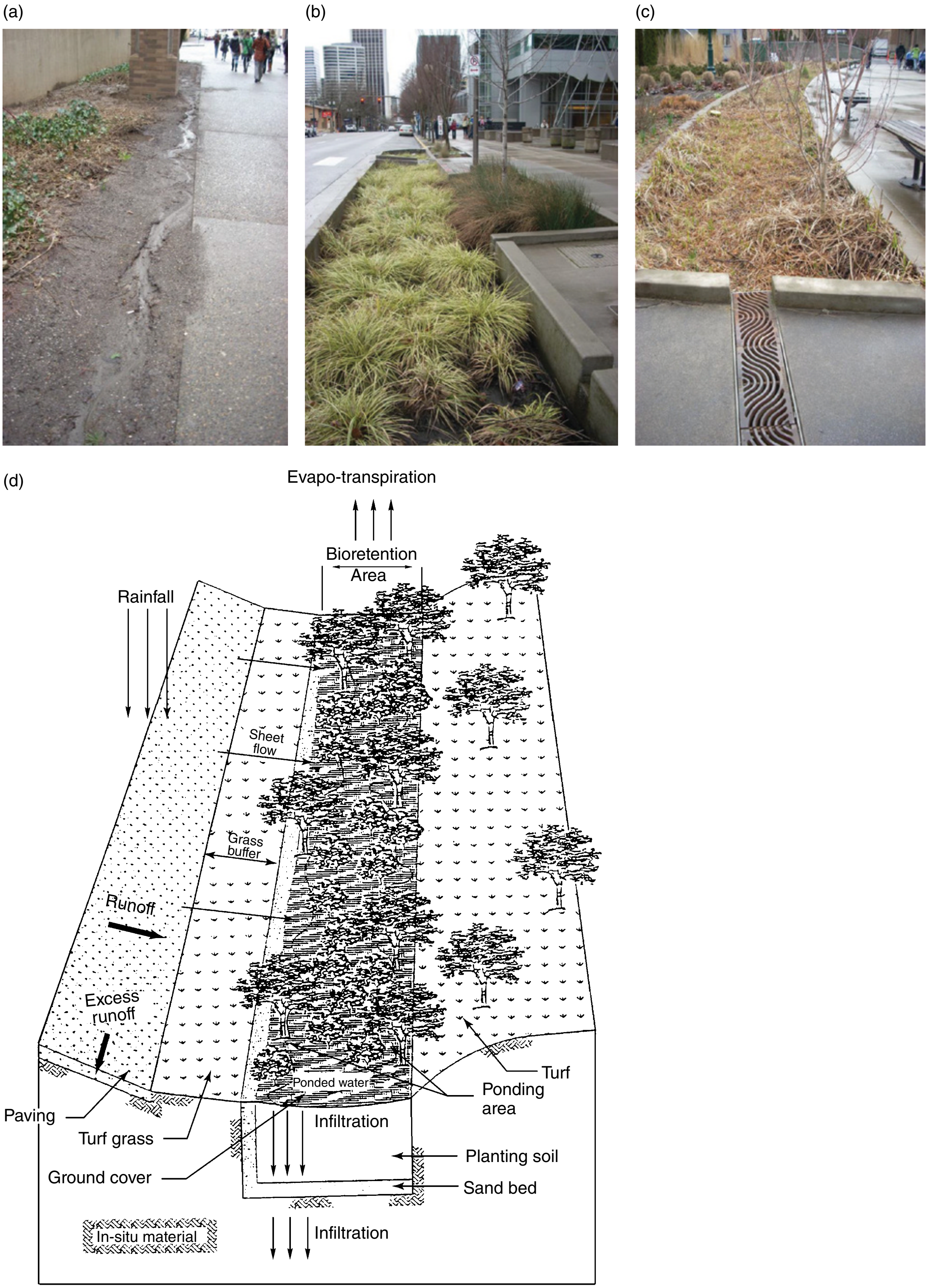


Figure 32.5 Illustrations of bioswales in Portland, Oregon. **(a)** Surface erosion and stormwater runoff with no bioswale treatment. **(b)** Street diversion of stormwater runoff into a bioswale. **(c)** Pavement diversion of stormwater runoff. *Source:* **(a–c)** Mark S. Ashton. **(d)** An example of a bioswale design. *Source:* Urban Water Group, Department of Civil and Environmental Engineering, University of Utah.

Rain gardens are designed to dissipate stormwater off of roofing and small paved areas; they are similar to bioswales, but for smaller runoff areas. They are designed to slow the velocity and improve groundwater recharge. Water may collect during heavy storms, but rain gardens do not store or retain water but instead dissipate it into the soil and beds of plants. Being smaller, rain gardens are ideal as drainages for individual house roofs and parking areas. Bio-retention installations, including rain gardens and bioswales, are increasingly used to maintain groundwater recharge and base flow, remove surface and groundwater pollutants, and reduce peak flows of stormwater runoff (Davis *et al*., 2009). A comprehensive set of field tests at the University of New Hampshire Stormwater Center documented 97% removal of total suspended solids through bioretention, with results duplicated at Villanova (Davis *et al*., 2009; University of New Hampshire Stormwater Center, 2006).

Enhanced tree pits or **tree trenches** are the last GSI that concern trees and vegetation with a silvicultural application. Tree pits are designed to collect stormwater that is diverted from roads and filters through tree roots and surrounding soil mix (Fig. 32.6). To the untrained eye, they resemble street trees planted in the usual rows, but actually they are designed to trap sediment and pollutants, and maximize water infiltration directly into the soil or indirectly into a stormwater sewer. They have demonstrated a savings in stormwater management calculated at $18 per tree per year that, taken at the scale of a city that has thousands of trees, can save hundreds of

(a)

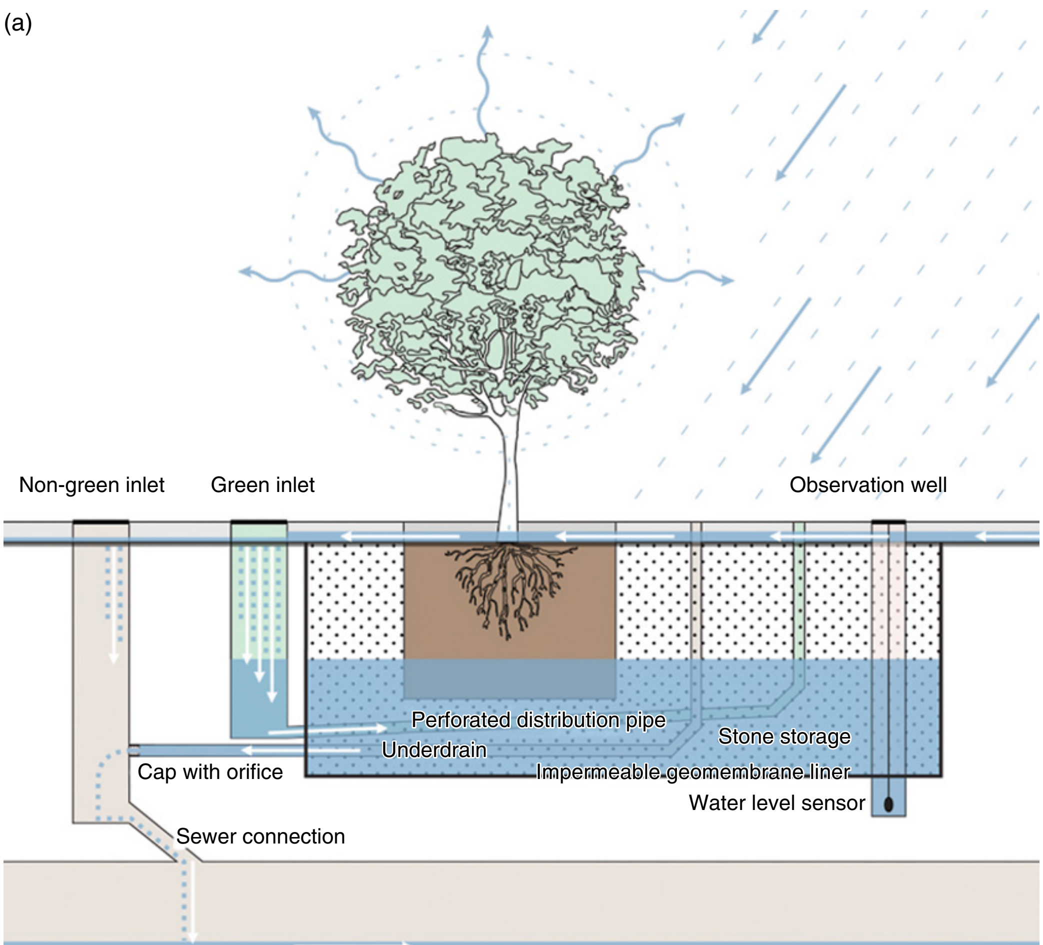


Figure 32.6 **(a)** Tree trenches with a cap between the under drain and the sewer inlet can be designed to either promote infiltration of stormwater into the ground or to delay its eventual release into the sewer system. For infiltration into the ground, stormwater runoff flows underground through a perforated distribution pipe into a layer of gravel or stone, watering the trees and slowly infiltrating into the ground through a bottom layer of sand. For diversion, stormwater can instead be designed to be temporarily retained and infiltration prevented by an impermeable liner that forces excess water that is collected through a distribution pipe that slowly releases it to the sewer system. *Source:* Green City Clean Waters. Reproduced with permission from Philadelphia Water.

(Continued)

(b)

Figure 32.6 (Continued) **(b)** A street tree planting using tree trenches with an interconnected stormwater storage system in New York City *Source:* Mark S. Ashton.

Figure 32.7 The slope adjacent to a walk way (slope to left of picture) in New Haven, CT, that has been purposely allowed to regenerate naturally to create a perpetual stand in stem exclusion. This is done by continually removing the tallest pole-sized trees at periodic intervals to: (1) allow light through the canopy to the groundstory to encourage forbs, grasses, and new recruits; (2) prevent trees from growing into the power lines; and (3) ensure that the stems on the slope do not become unstable and topple over. The seed sources are from nearby oak trees dispersed by squirrels, cherry dispersed by birds, and birch and tulip-poplar dispersed by wind. The design creates a small linear vegetation buffer between the street and building, maximizes interception and infiltration of precipitation, builds soil carbon and fertility, and creates wildlife habitat. Prior to 2000 the slope was denuded through weekly mowing and fertilization, with high surface runoff and erosion. *Source:* Mark S. Ashton.

thousands to millions of dollars in water treatment (Dwyer *et al.*, 1992).

Cheaper versions can be created with very little effort in different parts of a roadside or street curb (Fig. 32.7) by allowing the green space to naturally regenerate. Tree-dominated curbs can be used to stabilize slopes or to mitigate stormwater runoff from the road surface by guiding runoff into vegetated edges.

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Common and Scientific Names of Trees and Shrubs Mentioned in the Text

Common name	**Scientific name**
Acacia	*Acacia* spp. Miller
Alang-alang	*Imperata cylindrical* (L.) P. Beauv.
Albizia	*Albizia* spp. Durazz
Alder, red	*Alnus rubra* Bong.
Sitka	*Alnus viridis* (Chaix) D.C.
Apple	*Malus domestica* Borkh.
Ash, mountain (eucalypt)	*Eucalyptus regnans* F. Muell.
Ash, white	*Fraxinus americana* L.
green	*Fraxinus pennsylvanica* Marsh
Oregon	*Fraxinus latifolia* Benth.
tropical	*Fraxinus uhdei* (Wenzig) Lingelsh.
Aspen, bigtooth	*Populus grandidentata* Michx.
quaking	*Populus tremuloides* Michx.
Autumn-olive	*Eleaegnus umbellata* Thunb.
Avocado	*Persea Americana* Mill.
Bald-cypress	*Taxodium distichum* (L.) Rich.
Balsa	*Ochroma pyramidale* (Cav. Ex Lam.) Urb.
Babussa palm	*Attalea speciosa* Mart.
Basswood, American	*Tilia americana* L.
Beech, American	*Fagus grandifolia* Ehrh.
European	*Fagus sylvatica* L.
Birch, black	*Betula lenta* L.
gray	*Betula populifolia* Marsh.
paper	*Betula papyrifera* Marsh.
yellow	*Betula alleghaniensis* Britton
Bittersweet	*Celastrus orbiculatus* Thunb.
Blackberries	*Rubus* spp. L.
Black-gum	*Nyssa sylvatica* Marsh.
Boxelder	*Acer negundo* L.
Blueberries	*Vaccinium* spp. L.
Breadfruit	*Artocarpus altilis* (Parkinson) Fosberg
Buckeye, Ohio	*Aesculus glabra* Willd.
Cacao	*Theobroma cacao* L.
Cardamom	*Elettaria ensal* (Gaertn.) Abeyw.
Catalpa	*Catalpa speciosa* Warder ex. Engelm.
Cecropia	*Cecropia* spp. Loefl.
Cedar, Alaska yellow	*Chamaecyparis nootkatensis* (D. Don.) Spach
Atlantic white	*Chamaecyparis thyoides* (L.) Britton, Sterns & Poggenb.
northern white	*Thuja occidentalis* L.
Port Orford	*Chamaecyparis lawsoniana* (A. Murray) Parl.
Spanish	*Cedrela odorata* L.

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Cheatgrass	*Bromus tectorum* L.
Cherries	*Prunus avium* L.
Cherry, black	*Prunus serotina* Ehrh.
choke	*Prunus virginiana* L.
pin	*Prunus pensylvanica* L.f.
Chestnut, American	*Castanea dentata* (Marsh.) Borkh.
European	*Castanea sativa* Mill.
Cinnamon	*Cinnamomum verum* J. Presl
Climbing fern	*Lygodium japonicum* Sw.
Coconut palm	*Cocos nucifera* L.
Coffee	*Coffea* spp. L.
Cottonwood, black	*Populus trichocarpa* (Torr. & Gray) Brayshaw
eastern	*Populus deltoides* Bartr. (ex Marsh.)
Currant and gooseberry	*Ribes* spp. L.
Dipterocarps	*Dipterocarpus* spp. C. F. Gaertn.
Dogwood, flowering	*Cornus florida* L.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Durian	*Durio zebithinus* L.
Dwarf mistletoe	*Arceuthobium* spp. M. Bieb.
Elms	*Ulmus* spp. L.
Erythrina	*Erythrina* spp. L.
Eucalypts	*Eucalyptus* spp. L'Hér
Figs	*Ficus* spp. L.
Firs, balsam	*Abies balsamea* (L.) Mill.
European silver	*Abies alba* (Mill.)
grand	*Abies grandis* (Dougl.) Lindl.
noble	*Abies procera* Rehd.
Pacific silver	*Abies amabilis* (Dougl.) Forbes
red	*Abies magnifica* A. Murr.
subalpine	*Abies lasciocarpa* (Hook.) Nutt.
white	*Abies concolor* (Gord. & Glend.) Lindl. (ex Hildebr.)
Ginger	*Zingiber officinale* Roscoe
Gmelina	*Gmelina arborea* L.
Gum, black	*Nyssa sylvatica* Marsh
Hackberry	*Celtis* spp. L.
Hay-scented fern	*Dennstaedtia punctilobula* (Michx.) T. Moore
Hazel	*Corylus* spp. L.
Hemlock, eastern	*Tsuga canadensis* (L.) Carr.
mountain	*Tsuga mertensiana* (Bong.) Carr.
western	*Tsuga heterophylla* (Raf.) Sarg.
Hickory, pignut	*Carya glabra* (Mill.) Sweet
mockernut	*Carya tomentosa* (Poir.) Nutt.
shagbark	*Carya ovata* (Mill.) K. Koch
water	*Carya aquatic* (Michx. f.) Nutt.
Hinoki	*Chamaecyparis obtuse* Endl.
Hornbeam, European	*Carpinus betulus* L.
Hop-hornbeam, eastern	*Ostrya virginiana* (Mill.) K. Koch.
Horse-chestnut	*Aeculus hippocastanum* L.
Incense-cedar, California	*Libocedrus decurrens* Torr.
Indian almond	*Terminalia catappa* L.
Jak	*Artocarpus heterophylla* Lam.
Japanese knotweed	*Fallopia japonica* (Houtt.) Ronse Decr.
Juniper, western	*Juniperus occidentalis* Hook.
Kapok	*Ceiba pentandra* (L.) Gaertn.

Kudzu	*Pueraria* spp. DC.
Larch, European	*Larix decidua* L.
Japanese	*Larix leptolepis* (Sieb. & Zucc.) Gord.
Siberian	*Larix sibirica* Ledeb.
western	*Larix occidentalis* Nutt.
Laurel	*Laurus nobilis* L.
Locust, black	*Robinia pseudoacacia* L.
Luan	*Shorea* spp. Roxb. ex C. F. Gaertn.
Macaranga	*Macaranga* spp. Thouars
Madrone, Pacific	*Arbutus menziesii* Pursh
Mahogany, African	*Entandrophragma* spp. Juss.
Honduran, big leaf	*Swietenia macrophylla* King.
Maize	*Zea mays* L.
Mango	*Mangifera indica* L.
Mangosteen	*Garcinia mangostana* L.
Mangrove	*Rhizophoraceae* spp. Pers.
Manzanita	*Arctostaphylos columbiana* Piper
Maple, bigleaf	*Acer macrophyllum* Pursh
red or soft	*Acer rubrum* L.
silver	*Acer saccharinum* L.
sugar	*Acer saccharum* Marsh.
vine	*Acer circinatum* Pursh
Melaleuca	*Melaleuca* L.
Meranti	*Shorea* spp. Roxb. Ex C. F. Gaertn.
Mountain laurel	*Kalmia latifolia* L.
Mugwort	*Artemesia vulgaris* L.
Musclewood	*Carpinus caroliniana* Walter
Myrtle	*Melaleuca* spp. L.
Neem	*Azadirachta indica* A. Juss.
Oak, bear	*Quercus ilicifolia* Wangenh.
black	*Quercus velutina* Lam.
blue	*Quercus douglasii* Hook. & Arn.
bur	*Quercus macrocarpa* Michx.
California black	*Quercus kellloggii* Newb.
California (coast) live	*Quercus agrifolia* Née
canyon live	*Quercus chrysolepis* Liebm.
cherrybark	*Quercus falcata* var. *pagodaefolia* Ell.
chestnut	*Quercus prinus* L.
cork	*Quercus suber* L.
English	*Quercus robur* L.
Evergreen, holm	*Quercus ilex* L.
Gambel	*Quercus gambelii* Nutt.
Interior live	*Quercus wislizeni* A. DC.
live	*Quercus virginiana* Mill.
northern red	*Quercus rubra* L.
Nuttal	*Quercus nutallii* Buckley
Oregon	*Quercus garryana* Douglas ex Hook.
overcup	*Quercus lyrata* Walt.
pin	*Quercus palustris* Muenchh.
post	*Quercus stellata* Wangenh.
scarlet	*Quercus coccinea* Muenchh.
sessile	*Quercus petraea* (Mattuschka) Liebl.
Shumard	*Quercus shumardii* (Buckland)
silk	*Grevillea robusta* A. Cunn ex R. Br.

southern red	*Quercus falcata* Michx.
swamp chestnut	*Quercus michauxii* Nutt.
swamp white	*Quercus bicolor* Willd.
water	*Quercus nigra* L.
white	*Quercus alba* L.
willow	*Quercus phellos* L.
Oil palm	*Elaeis guineensis* Jacq.
Palmetto, saw	*Serenoa repens* (Bartr.) Small
Pears	*Pyrus* spp. L.
Pecan	*Carya illinoensis* (Wagenh.) K. Koch
Peaches	*Prunus persica* (L.) Batsch
Pepper (vines), black	*Piper nigrum* L.
Persimmon	*Diospyros virginiana* L.
Pine, Aleppo	*Pinus halepensis* Mill.
bishop	*Pinus muricata* D. Don
Caribbean	*Pinus caribaea* Mor.
Digger	*Pinus sabiniana* Dougl.
Durango	*Pinus durangensis* Mart.
dwarf pitch	*Pinus rigida* Mill.
eastern white	*Pinus strobus* L.
foxtail	*Pinus balfouriana* Balf.
jack	*Pinus banksiana* Lamb.
Jeffrey	*Pinus jeffreyi* Grev. & Balf.
jelecote	*Pinus patula* Schl. & Cham.
limber	*Pinus flexilis* James
loblolly	*Pinus taeda* L.
lodgepole	*Pinus contorta* Dougl. ex Loud.
longleaf	*Pinus palustris* Mill.
Monterey or radiata	*Pinus radiata* D. Don.
pinyon	*Pinus edulis* Englem.
pitch	*Pinus rigida* Mill.
pond	*Pinus serotina* Michx.
ponderosa	*Pinus ponderosa* Laws.
red or Norway	*Pinus resinosa* Ait.
Rocky Mountain bristlecone	Pinus *aristata* Engelm.
sand	*Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg.
Scotch, Scot's	*Pinus sylvestris* L.
shortleaf	*Pinus echinata* Mill.
slash	*Pinus elliottii* Engelm.
sugar	*Pinus lambertiana* Dougl.
southwestern white	*Pinus strobiformis* Engelm.
Virginia	*Pinus virginiana* Mill.
western white	*Pinus monticola* Dougl.
whitebark	*Pinus albicaulis* Engelm.
Poplar, aspen	*Populus tremuloides* Michx.
cottonwood	*Populus trichocarpa* Torr. And A. Gray
hybrid	*Populus deltoides* W.Bartram ex Marsh. *x Populus nigra* L.
Rambutan	*Nephelium lappaceum* L.
Raspberries	*Rubus idaeus* L.
Redcedar, eastern	*Junipera virginiana* L.
western	*Thuja plicata* Donn ex D. Don
Redwood	*Sequoia sempervirens* (D. Don) Endl.
Rhododendron	*Rhododendron ferrugineum* L.
Rosewood	*Dalbergia nigra* (Vell.) Allemão ex Benth.

Rubber tree	*Hevea brasiliensis* (A. Juss.) Muell.
Sagebrush	*Artemesia tridentate* Nutt.
Sal	*Shorea robusta* Gaertn. F.
Sarsaparilla	*Smilax* spp. L.
Sassafras	*Sassafras albidum* (Nutt.) Nees
Sequoia, big-tree or giant	*Sequoiadendron giganteum* (Lindl.) B
Silk-oak	*Grevillea robust* Cunn.
Spruce, black	*Picea mariana* (Mill.) B.S.P.
blue	*Picea pungens* Engelm.
Engelmann	*Picea engelmannii* Parry
Norway	*Picea abies* (L.) Karst.
red	*Picea rubens* Sarg.
Sitka	*Picea sitchensis* (Bong.) Carr.
white	*Picea glauca* (Moench.) Voss.
Sugarberry	*Celtis laevigata* Willd.
Sugi	*Cryptomeria japonica* D.Don
Sumac	*Rhus* spp. L.
Sweet-gum	*Liquidambar styraciflua* L.
Sycamore	*Platanus* spp. L.
Tamarack	*Larix larcina* (Du Roi) K. Koch
Tanoak	*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.
Tea	*Camellia* spp. L.
Teak	*Tectona grandis* L.f.
Thimbleberry	*Rubus parvifloris* Nutt.
Tree of heaven	*Ailanthus altissima* (Mill.) Swingle
Tulip-poplar	*Liriodendron tulipifera* L.
Tupelo, gum	*Nyssa sylvatica* Marsh.
water	*Nyssa aquatic* L.
Walnut, black	*Juglans nigra* L.
White-cedar, Atlantic	*Chamaecyparis thyoides* (L.) B.S.P.
northern	*Thuja occidentalis* L.
Willow, dwarf	*Salix herbacea* L.
weeping	*Salix babylonica* L.
Wiregrass	*Aristida stricta* L.
Witch-hazel	*Hamamelis virginiana* Gronov. ex L.
Yellow-poplar	*Liriodendron tulipifera* L.
Yellow star thistle	*Centaurea solstitialis* L.
Yerba mate	*Ilex paraguariensis* A. St. Hil.
Yew, Pacific	*Taxus brevifolia* Nutt.

Glossary of Terms

Abscisic acid a common hormone that promotes dormancy in seeds and slows plant growth

Acute usually referring to a single large disturbance impact to a forest

Acute degradation a one-time impact to the forest and vegetation such as land clearance that eliminates the vegetation. It is usually severe enough to be a form of **physiochemical degradation** that affects soil function and fertility

Adaptive management managing continuously changing biological and social circumstances such that silvicultural prescriptions remain flexible in space and time

Additionality management that purposely intends to change behavior from the normal business-as-usual activities and thereby saves carbon emissions

Advance regeneration seedlings or seedling sprouts that germinate and establish in the forest understory and are released after a canopy disturbance (synonym: advance reproduction)

Adventitious buds buds that arise within reorganizing callus tissue after injury

Afforestation the planting of trees on lands that never had forests (e.g., natural grasslands)

Age class trees within a given range of ages (e.g., 10–20 years old)

Aggregated distribution where **reserve trees** are retained in patches of intact groups of trees within the stand (synonyms: patch retention, patch reserves, group retention, or group reserves)

Agri-silvicultural systems agroforestry systems that integrate trees with agricultural crops (usually arable)

Agroforestry when trees are mixed on the same land with food crops or pasture for domestic animals

Air-pruning containers with holes in the bottoms so that there is air beneath them; when the roots reach the air, they stop growing, but retain the capacity to resume when planted in contact with soil

All-aged a forest stand that includes four or more effective age classes of trees (see **cohort**)

Alleopathic effects chemical leachate from leaf litter and root exudate of certain species that inhibit the progeny of other species, or sometimes its own, from regenerating

Alley cropping a form of **permanent agroforestry** where trees are planted in rows and agricultural crops are planted in between

Apical control the inhibition (or control) of lateral buds and their growth by the terminal bud or stem leader of a tree (synonym: apical dominance)

Area method of regulation a form of forest-management regulation that consists of dividing the total forest area into as many equally productive units as there are years in the planned rotation, and harvesting one unit each year

Auxins plant hormones that are present throughout the plant's growth, and regulate its organ development. (For example, indolacetic acid (IAA) is primarily found in the tips of the stems and young leaves. It is important in orienting the stem and leaves toward light. Indolebutyric acid (IBA), another auxin, is important and is often used to stimulate rooting.)

Avoided deforestation protecting intact forests, thus protecting stored carbon that would otherwise be released from land clearance or logging

Backfires a form of prescribed burn that burns against the prevailing wind

Balanced meaning that an equal area is apportioned to each age class within the stand

Balanced all-aged meaning that an equal area is apportioned to each of four or more age classes within the stand using the **selection regeneration method**

Bare-root seedlings raised in soil beds within an open field for future out-planting

Basal area the cross-sectional area in square feet (or square meters) of the stem at DBH (4.5 ft)

Basal bark treatment applying oil solutions of herbicides in a continuous band on the bark at the ground-line around the base of the tree or shrub

Bedding and mounding reshaping the soil surface by plowing or scraping to create low ridges in wet places or shallow trenches to collect water in dry areas (synonym: bedding)

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Bench cuts a form of pruning in fruit and nut trees that removes all the vegetative vigorous upright shoots back to the **scaffold branches** of the original tree branching framework

Best management practices (BMPs) the term that refers to the methods used to mitigate impacts of the harvesting operation on the soils, hydrology, aesthetics, and wildlife habitat of a stand (synonym: **conservation management practices**)

Biochemical selectivity enzymatic resistance of some plants to herbicides while others do not have it

Biological control a form of **direct control** that involves the introduction or encouragement of biotic agencies that combat damaging organisms to target tree species or forests

Bioswales a stormwater mitigation technique designed as an alternative to storing the water underground in a tank and instead allowing the water to partially infiltrate into the subsurface soil of an area planted to woody and herbaceous vegetation

Branch bark ridge the zone of compression of bark and underlying wood between the branch and the central bole or stem of the tree

Branch collar the swelling at the base of the branch around the union between the central stem of the tree and the branch

Brashing low pruning to allow more easy access through a stand, especially in dense stands of species such as spruce, with many stiff branches

Breeder's seed seed from the original propagator of the variety desired for cultivation

Broadcast burning a technique of controlled burning that is associated with controlling vegetation or preparing a site for natural regeneration or planting; it is applied as uniformly as is possible across the whole stand area

Broadcast seeding scattering seeds uniformly over the area to be restocked

Browse the buds, twigs, and leaves of woody plants that serve as a food source throughout the year for such species as deer, elk, moose, hares, beaver, and grouse

Buried seed seeds dispersed by wind, water, or animals, and that settle on the forest floor (often beneath closed forest canopies), become buried with leaf litter and remain dormant for many years until an environmental trigger (e.g., change in temperature, light, soil moisture) promotes germination

Cable-yarding the process of lifting the logs into the air and moving them to a landing on a road using a stationary engine

Callus tissue a kind of meristem that can differentiate into various kinds of cells; the callus wood forms the cambium

Cambium the zone of meristem cells that encircles tree stems beneath the bark, and divides to form the **phloem** on the outside and **xylem** and other wood tissues on the inside; it is defined as **secondary growth**

Canopy stratification the arrangement of the tree crown structure within a forest. Where crowns are vertically positioned beneath each other upon progressing from the canopy to the understory, canopy stratification can be regarded as high

Certified seed the seed that nurseries sell to the public, farmers, or tree companies to use for general cultivation; when it is called certified seed it usually means that the pedigree can be traced back to the original breeder

Chemical girdling **frilling** with an application of **herbicide**; commonly called hack-and-squirt

Chronic usually refers to continuous or repeated disturbance impacts that are often degrading a forest's structure and composition

Chronic degradation is a form of natural or anthropogenic disturbance that repeatedly impacts the forest sufficient to permanently alter its composition and structure

Chronological age the true age of the plant or tree

Cleaning a **release operation** in which operations focus on removing only the overtopping vegetation around the selected crop trees

Clearcutting (the true) method of regeneration stands that originate as a single age class that have been established following a complete harvest and site treatment that creates a **lethal disturbance**. Reproduction is from seeds germinating *after* the clearing operation either coming from outside the stand (e.g., disseminated by wind, small birds, bats) or *in situ* (e.g., buried seed bank, serotiny). (Synonyms: **complete clearcutting or silvicultural clearcutting**)

Clearwood wood that is knot-free

Clonal orchard an intensively managed plantation of trees (usually genetically "improved") that are maintained in a low form by coppicing in order to clonally harvest young shoots for vegetative propagation

Close pruning method of **pruning** side or lateral branches from a dominant central stem that consists of cutting into the **branch collar** parallel to the main stem but not quite flush to the stem. It therefore cuts through the branch collar

Coarse woody debris a term used to define dead stems and branch wood that is considered large and that is found on the forest floor

Codominant in reference to the **Kraft Crown Class Classification** denoting trees with crowns forming the general level of the crown cover and receiving full light from above but comparatively little from the sides; usually with medium-sized crowns more or less crowded on the sides

Cohort contains all of the trees that had been established at a specific time, usually following a forest disturbance. For example, if a stand was partially burned, killing half of the trees, the seed fall for next year's regeneration would likely produce enough seedlings to cover the entire stand. Those new seedlings would be called a cohort. However, if that stand had been burned so badly that only a few trees survived, it might take 30 years for the seedlings to become established across the stand. Even though there may be a span of tree ages from 1 to 30, these trees are also a cohort. The specific age is not important, it is the disturbance event that creates or releases the new cohort that matters

Commercial clearcut the term that it is often used to describe logging operations in which only the merchantable trees are cut but bears no resemblance to the silvicultural definition

Commercial thinning thinnings that produce a net income from the treatment

Common garden trees of known provenance are grown in uniform environmental soil conditions, and are carefully spaced to provide the same available growth resources of water, nutrients, and light, to evaluate growth differences among species, provenance, race, or variety

Compartmentalization the complete process of sealing off infections chemically, by resins, by occlusion of callus and stemwood growth, and from the cell wall structures and densities of ray parenchyma

Complementary interactions plants or trees that compete for the same resource that are very compatible (e.g., the disparity in tree growth between seedlings of quick-growing, shade-intolerant species, and seedlings of shade-tolerant species that begin growth more slowly)

Compression methods of planting holes are made for the plants by pushing the soil aside with sharp instruments into the ground. After the tree is inserted, the soil is pressed back around its roots (e.g., bar-slit or grubhoe-slit)

Compound coppice stands several age classes of standards usually constituting a multi-aged stand within a coppice. This is the equivalent of **irregular** for seedling-origin even-aged methods of regeneration

Conservation management practices (CMPs) the term used to refer to the methods of mitigating impacts of the harvesting operation on the soils, hydrology, aesthetics, and wildlife habitat of a stand (synonym: **best management practices**)

Containerization seedlings raised in pots, tubes, blocks, and plugs within an enclosed space, usually a shadehouse or greenhouse for future out-planting

Contouring a site protection treatment to mitigate or prevent surface soil erosion by creating walls, terraces, hedges, or arranging woody debris along the horizontal surface of the topography

Contrast a wildlife habitat term used to define the amount of difference between two adjacent stands

Controlled burn a general term (also known as prescribed burning) used to reduce hazards from wildfire, to prepare the site for regeneration, or to control vegetation as a post-establishment treatment

Coppice method of regeneration an even-aged stand that grew from vegetative sprouts (see **simple coppice method of regeneration**)

Coppice-with-standards system in which small numbers of scattered promising trees of seedling origin, or **standards**, are reserved above stands of coppice regeneration method. The standards are left to grow for two or more short coppice rotations

Corridor or corridor-shaped stands stands with long rectangular or linear shape promoting edge and heterogeneity of habitat over interior and uniform habitat

Cover any vegetation that shelters wildlife from predators (escape or hiding cover) or climatic extremes (thermal cover)

Cover type a delineated area with a uniform composition of vegetation

Covert a wildlife term used to define any area where at least three habitats meet at a point

Crop-tree thinning (management) a type of **crown thinning** developed for mixed-species hardwood stands where there is a very large difference between the value of crop trees and the rest of the stand

Crown cleaning pruning method that removes dead and dying limbs, usually done in mature shade trees of urban areas

Crown competition factor the relationship between crown size (crown width, crown projection area, crown volume) and tree diameter, and can be defined as the area available to the average tree in a stand compared to the maximum area used by an open grown tree with the same diameter

Crown differentiation as weaker trees are crowded by their taller associates, their crowns become increasingly misshapen and restricted in size. Unless freed by random accidents or deliberate thinning, these trees gradually become overtopped and ultimately die. In this constant attrition, the weaker members of an age class are progressively submerged, and the strongest forge ahead

Crown shyness example of self-pruning of the finer twigs between and within canopy tree crowns, caused by periodic or continuous branch abrasion from wind

Crown thinning trees are removed from the middle and upper crown classes, in order to open up the canopy and favor the development of the most promising crop trees of these same classes (synonym: **thinning** from the middle)

Crown wood the xylem wood laid down around the pith and within the youngest part of the tree that is strongly influenced by proximity to the growth regulators on the tree crown (synonym: **juvenile wood**)

Current annual increment (CAI) the most recent year of tree growth as measured by bole diameter increment or stem volume increment

Cuticle the waxy covering on the entire leaf surface

Cut-surface treatment involves application of a water-soluble herbicide to the surface of freshly cut stumps

Cut test dissects a sample of seed to examine the proportion of the seed with live tissue

Cutting cycle the period between each entry into the stand within the **selection regeneration method**

Cuttings a form of vegetative propagation in which shoots that, when placed in soil, will take root and become new plants

Cytokinin a hormone that counteracts abscisic acid in seed germination by promoting cell division

Damping-off the phenomenon whereby a group of fungi (*Fusarium* spp., *Phytophora* spp.) will kill young germinating seedlings whose fleshy growth will rot and fall over in damp, humid soil conditions

Dead knots **knots** that are formed after branches have died (synonym: **encased knots** or **black knots**)

Decurrent form the growth of trees when their branches begin roughly horizontal but then curve upward to become vertical. The main branches on trees of decurrent species grow so large in size that they may nearly equal the diameter of the original main stem; in many cases, a main stem cannot be identified in the upper part of a mature tree

Density-dependence species establish and do better away from the parent tree because they are less susceptible to their host-specific insects and diseases when surrounded by unrelated trees that are inhospitable to those insects and diseases

Den tree living trees with cavities that animals use for shelter and protection

Diameter-limit thinning type of **dominant thinning** in which a minimum target diameter is chosen, and all trees larger than that diameter are cut. In mixed-species stands, different target diameters may be used for different species

Differential wetting the process that allows **herbicide** to settle on the leaves of some plants and not others in **foliar applications**

Direct control refers to control of damaging organisms (i.e., insects, disease, invasive plants) involving attacking the insects or pathogens themselves, either with pesticides or with various methods known as **biological control**

Direct seeding a technique of artificial regeneration by sowing of seeds to establish forest stands

Dispersed distribution where individual reserve trees are scattered across the stand area

Dissolved organic matter (DOM) processes of litter decomposition that promote organic matter in solution that can infiltrate the mineral soil

Dominant in reference to the **Kraft Crown Class Classification** where trees with crowns extending above the general level of the crown cover, and are receiving full light from above and partly from the sides; larger than the average trees in the stands and with crowns well developed but possibly somewhat crowded on the sides

Dominant thinning the largest trees are removed in order to promote the growth of trees of lower crown classes (synonym: selection thinning or thinning from above)

Dormancy a state in which seeds and other structures (such as underground stems) reduce their metabolic activities to a minimum level during unfavorable conditions (e.g. low temperature, drought) so as to survive until conditions improve

Dormant buds buds that did not develop into lateral shoots but remained dormant, growing outward with the **cambium** to maintain positions just beneath the bark (shoots almost invariably develop from lateral buds that were originally formed on the leading shoot of the seedling – these do not)

Double-hacking a kind of **girdling** in which a horizontal line of chips is removed by striking two downward blows. The second is made above the first so that the chip of bark may be pried entirely out of the cut with a twist of the ax handle

Drought-avoiders tree species that avoid internal moisture stress that could cause the foliage to be permanently damaged, but do so at the expense of productivity because photosynthesis cannot continue if the stomata are closed. They do this by losing their leaves (deciduous) or dying back

Drought-endurers tree species that leave their stomata open and continue photosynthesis at the risk of suffering permanent wilt damage if the period of moisture stress is not short lived. Usually such species can endure drought because they are deep rooted, with protective and water-use-efficient structures that allow them to conserve water

Dug-hole planting methods the soil is actually removed and set aside to be repacked around the roots after the seedlings are arranged in the hole (e.g., center hole, side hole, wedge)

Ecosystem management adaptation strategies to help forest ecosystems accommodate to change and mitigation strategies that use forests to reduce and moderate ecosystem change. The two types of approaches can be integrated at a landscape scale by applying them in different but contiguous stands over time. Compared to the norm, there is a stricter adherence to imitating natural disturbance regimes and their biological legacies

Edge effect a wildlife habitat term used to define the adjacency of two or more habitats that many species of wildlife need on a daily basis

Edge species wildlife species dependent upon edge habitat (see **edge effect**)

Effective age the number of years since the trees were free to start rapid growth and development into a new forest

Emergent trees with crowns extending well above the general level of the canopy, so much so that the bottom of the crown is above the canopy

Engineered wood products pieces of wood that are glued together to increase length or thickness. Wood can also be shredded and glued together in flat panels such as oriented-strand board

Enhanced tree pits designed to collect stormwater that is diverted from roads and into pits with planted trees. The water filters through tree roots and surrounding soil mix

Enrichment planting planting seedlings or cuttings within a regenerating stand to add a species or to increase stocking to a desired level for successful regeneration

Epicormic branching where new shoots develop from **dormant buds** under the bark of the main stem, or from new adventitious buds that form in the callus tissue around the pruning wound or site of injury

Epigeal seeds of species that germinate and raise their cotyledons aboveground as the seed germinates to act as the first photosynthetic organs

Even-aged when the range of ages of trees within a cohort is very narrow, the new aggregation is regarded as a single **age class** which is also **even-aged**. In this book "even-aged" and "single cohort" are synonymous (see also **effective age** and **chronological age**)

Excurrent form tree with growth that includes a main vertical stem that extends to the very top of the tree. The branches are distinctly smaller in diameter, growing in a roughly horizontal orientation

Exotic species a non-native species that is artificially introduced to an area

Extensive silviculture silviculture usually practiced over large areas using natural regeneration methods with low treatment inputs and relying almost entirely on the inherent fertility of soil and the capacity of the forest to self-regulate

Facilitative interactions where the actual combination of two species has a higher biomass yield than any spacing density of either species as a monoculture (e.g., nitrogen-fixing species mixed with a non-nitrogen-fixing species)

Family selection trees arising from each female parent through open pollination

Fertigation fertilizers that are applied in solution during irrigation

Field capacity the amount of soil moisture or water content held in the soil after excess water has drained away and the rate of downward movement has decreased

Filling in filling in the gaps from initial plantings in a plantation by supplementary planting

Financial rotation the interval of time between regeneration and harvest with the goal of optimizing monetary return on capital under the soil rent principle which usually means highest **NPV**

Flanking fires a kind of prescribed burn in which the fire is set in lines parallel to the wind (synonym: quartering fires)

Fog-drip water dripping to the ground from trees or other objects which have collected the moisture from drifting fog and through condensation

Foliar application use of **herbicide** spraying for **release operations** that are usually designed to kill broadleaf woody species and herbaceous weeds

Forest ecosystem management (FEM) managing forests for all the biological fauna, flora, and functions that a forest performs (see **ecosystem management**)

Forest vegetation management (FVM) see **vegetation management**

Forwarder the machine used to carry logs to the landing

Forwarding and forwarding trails the process of carrying logs from the harvest site to the landing; a forwarding trail is a trail designed and used for carrying the logs to the landing

Foundation seed seed derived from plants in other nurseries that obtained seed from the original breeder

Free Air Carbon Exchange (FACE) experiments have been set up throughout the temperate realms and are designed to pump extra amounts of CO_2 and manipulate temperature over young stands of trees, and then monitor growth response

Free-form thinning applied to heterogeneous stands by any one of a combination of **low**, **crown**, and **dominant thinning**. This approach to thinning is spatially explicit, where in some parts of the stand

low thinning is applied, other parts crown thinning, and still other parts of the stand dominant thinning, with the goal of creating a more uniform stand structure and spacing after treatment

Free-to-grow regenerating stands where the desired species are in a condition from **release treatments** or from self-development in which they have no over-topping or competing vegetation and are deemed capable of forming a new forest

Frilling a form of **girdling** where the downward blade of the axe is used to cut uniformly around the circumference of the tree bole as a single overlapping line (synonym: single-hacking)

Genetically modified organisms (GMOs) organisms in which the genetic material (DNA) has been altered in a way that does not occur naturally by mating and/or natural recombination

Genotype the genetic make-up of an organism/plant

Geometric thinning trees to be cut or retained are chosen on the basis of a geometric spacing pattern, rather than on their species, stem quality, or canopy position. Examples are removing every other row of trees or removing alternate individuals from a row of trees (synonym: mechanical thinning)

Germination process by which the plant embryo within the seed resumes growth after a period of dormancy and the seedling emerges

Germination capacity a measure of seed viability by measuring the total proportion of seed that germinates

Germinative energy a measure of seed vigor and viability by testing the rate at which the seed germinates

Giberellins plant hormones that regulate cell elongation and stem growth

Girdling a notched ring or the removal of a ring of bark completely around the bole of a tree right up to and into the wood, bisecting the cambium

Grafting the process of uniting a hardy seedling root, called the stock, with a cut stem, called the scion

Greenhouse gas (GHG) gasses (e.g., carbon dioxide, methane, chlorofluorocarbons) that contribute to heating of the world's atmosphere by absorbing and emitting infrared radiation

Gross primary production (GPP) the total photosynthesis of a forest stand (or of any ecosystem)

Groundstory the vegetation at the ground surface including herbs, grasses, and ferns along with advance regeneration

Group selection a **selection regeneration method** in which a group of two to six canopy trees are removed, creating a large canopy opening that is approximately one to two tree heights in diameter

Group shelterwood a **shelterwood regeneration method** in which preparatory and or establishment cuts are first made to create appropriately sized canopy openings suited to the shade tolerance of the regeneration being established. These openings are then sequentially expanded upon over a relatively short period relative to the rotation such that gaps finally merge into each other

Growing stock the number and/or size of trees growing in a forest stand that meet the desired criteria for future composition, vigor, and growth

Growing space the area available for tree growth

Green stormwater infrastructure (GSI) the arrangement and use of vegetation and soils to mitigate stormwater (e.g., bioswales, tree pits, green roofs)

Guilds ecological groupings of tree species with similar reproductive or growth characteristics (e.g., species that all rely on buried seed bank could be considered an ecological guild) (synonym: functional groups)

Habitat an ecological area with a common structure and species composition of vegetation that creates desired living and reproductive space for associated (often unique) species of wildlife

Hardening off the gradual exposure of nursery seedlings and vegetative cuttings to drier or colder conditions in preparation for transplanting or lifting

Hard mast Seeds that are considered nuts and that serve as a food source for animals (e.g. oak, hickory, beech)

H:D ratio the relationship between total tree height to diameter at breast height (DBH) is a measure of taper to describe differences in tree growth form among individuals of a species and between species

Headfires a kind of prescribed burn that burns with the wind

Heading cut (topping) a form of **pruning** either made to young shoots (first year) that removes the top of a new shoot, promoting the vigorous release of the buds immediately toward the top end that result in lateral branching, or made in older wood to move the crown back into its allotted space

Heartwood the non-functional inner **xylem** wood that is older

Heeling in temporarily storing the roots of bare-root seedlings in buried trenches usually at the planting site until available for proper out-planting

Helicopter-logging the use of helicopters to lift and carry logs from the harvest site to the landing

Herbage the herbaceous groundcover that is available as forage for livestock or wildlife that includes the leaves, stem, and rhizomes of non-woody plants

Herbicide chemicals that are designed to kill a variety of plants in different ways and modes of application

Heritability an estimate of how much of the genetic diversity within a phenotype is due to genetic differences as compared to environmental differences

Heterozygous trees that are genetically variable

High forest a forest of seedling origin that attains reproductive maturity (high stature)

High-grading the removal of the most commercially valuable (usually larger trees) with no thought to their future replacement in the forest stand

Homozygous trees that are genetically uniform

Hybrid pairs or groups of species that naturally cross-pollinate within a genus

Hybrid vigor where the hybrid of two species has superior growth characteristics compared to either parent

Hydrophobic usually referring to soils that repel water rather than absorb it. Often associated with fire-baked soils and certain minerals within soils that promote surface runoff and erosion, rather than water infiltration

Hypogeal seeds with cotyledons that remain belowground when they germinate

Improved fallows rather than mixing crops and trees spatially, agricultural crops are grown in monocultures for several cycles, followed by a fallow period in which the regeneration of woody vegetation is managed to improve the efficiency and fertility of the soil

Indirect control refers to measures that make the circumstances less favorable to the damaging organism or more favorable to their hosts

Initial floristics a term coined by Frank Egler (1954) referring to the relatively synchronous release and/or establishment of regeneration after a disturbance

Integrated pest management (IPM) using ecological habitat treatments, in combination with the insects' or pathogens' known biology, to reduce harmful effects on a crop plant to a tolerable level and resorting to more intensive chemical and physical controls as a last resort

Intensively managed forest plantations (IMFPs) plantations with very rapid juvenile growth grown at very short rotations (e.g., 5 years)

Intensive silviculture silviculture practiced with high inputs of fertilizer, site preparation, and a reliance on planting

Interior species wildlife species dependent upon uniform habitat that is away from the **edge effect**

Intermediate in reference to the **Kraft Crown Class Classification**, trees shorter than those in the **codominant** and **dominant** classes but with crowns extending into the crown cover but receiving little direct light from above but none from the sides. Crowns are usually small and considerably crowded on the sides

Intermediate cutting **post-establishment treatments** that involve **release** or **thinning**

Irregular regenerating stands of **seed-tree** or **shelterwood** origin but with the retention of additional structures and age classes, making them spatially more heterogeneous. By implication, although there can be up to three age classes, they are distinctly **unbalanced**, with the most recent regenerating age class dominating the number and spatial area of the stand (see **seed tree with reserves** and **shelterwood with reserves**)

Juvenile wood the **xylem** wood laid down around the pith and within the youngest part of the tree that is strongly influenced by proximity to the growth regulators on the tree crown (synonym: **crown wood**)

Juxtaposition a wildlife habitat term used to describe the nature of the placement of two stands adjacent to each other

Knots branches that are encased in stem wood

Kraft Crown Class Classification a system used to define crown position and size within forest canopies: **dominant**, **codominant**, **intermediate** and **overtopped**

Landing the collection site where logs are picked up by trucks from a stand that is being harvested for commercial timber

Langsaeter's curve a hypothesized pattern of stand volume growth at different levels of stand density, as measured by basal area. It suggests that foresters have considerable flexibility in choosing thinning intensity to produce larger individual trees, without loss of overall stand-level production. However, it does not match reality. Instead, it is now apparent that these patterns are responses to variations in species and sites, and their interactions

Lateral buds and shoots buds formed along the new shoot usually in the axils of the newly formed leaves (also called axillary buds in these circumstances). They are embryonic shoots that have the potential to be released (often by an environmental trigger or stressor) to form new shoots and leaves or flowers dependent upon species and environment. Some of these buds can remain **dormant** for a very long time. The ability to control these buds to be released is defined as **apical control** or apical dominance

Layering vegetative reproduction that arises from living, low-hanging branches that have been partially buried in moist organic matter

Leaf area allocation method relationship between amounts of foliage or crown sizes and the accretion of wood using leaf-area index (LAI) as a proxy measure for the development of **balanced all-aged** stands

Leaf-area index (LAI) the sum of the leaf surface area through the canopy of a forest per unit ground area. Usually the number of leaves directly over a piece of ground in a closed canopied forest varies between 2 and 15, depending upon moisture, nutrient, and light limitations

Lethal disturbance a disturbance that kills all forms of vegetation on a site and physically disturbs the soil (see **sub-lethal**)

Liberation a **release operation** used to open up overtopping growing space to young stands that are below the seedling, sapling, or pole stage by removing older and larger trees

Lignotuber a woody swelling at the base of the tree originating from callus tissues formed within the axils of seedling cotyledons or leaves usually after injury from fire. They are characteristic of many eucalypts

Live-crown ratio (LCR) the stem length within the living branches divided by the total height of the tree, generally stated as a percentage

Live knots knots produced when the branches were alive (synonym: tight knots, intergrown knots, or red knots)

Live pruning pruning applied to living branches. Usually done in agroforestry, urban, and orchard circumstances but occasionally done for timber plantations (synonym: **green pruning**)

Low-density thinning an intensive crown thinning applied mainly in single-species conifer plantations and in natural conifer stands. The goal is to produce large, high-quality sawlogs very rapidly

Low forest a forest usually of vegetative origin that does not attain reproductive maturity before harvest and therefore is usually of low stature

Low thinning trees are first removed from the understory and other lower crown classes, and the removals can progress further into the higher crown classes, depending upon the intensity of thinning (synonym: thinning from below)

Maintenance respiration the use of a plant's energy to sustain the basic function of living cells by rebuilding protein molecules, repairing cell membranes, and keeping the plant alive

Mass selection where promising **phenotypes** are identified from the wild population (synonym: plus tree selection)

Mast crops the fruit of forest trees that produce nuts. A mast year is a year when abundant nuts are produced (synonym: hard mast)

Mature wood **xylem** wood that is produced within the bole of a tree below and away from the influence of the crown

Mean annual increment (MAI) the total growth increment, usually measured as volume or diameter, of a tree or population of trees (stand), divided by the age of the tree or population of trees

Methods of reproduction refers to treatments of stand and site during the period of regeneration and establishment (synonym: methods of regeneration)

Mixed stand a stand of trees represented by two or more species

Multi-aged a stand of trees that includes two or three effective **age classes** (or **cohorts**)

Multipurpose tree species trees species with many products and values (e.g., timber, fodder, resin, fruit, soil fertility) often used in **agroforestry** systems

Native species plants and animals that have evolved over geologic time within a given area naturally (synonym: indigenous species)

Natural regeneration seedlings, advance regeneration, seed, and vegetative sprouts that originate from within or from adjacent forest stands

Natural regeneration methods methods of obtaining **natural regeneration** through cuttings that simulate different kinds of canopy and groundstory disturbance at different spatial and temporal scales within a stand (see **clearcutting**, **seed-tree**, **shelterwood**, **selection** and **coppice** natural regeneration methods)

Natural target pruning a method of pruning lateral branches that consists of cutting the branch at the outer edge of the **branch collar** (the edge of the collar being the "target")

Net ecosystem production defined as the difference between total gross primary production and total ecosystem respiration (plant, animal, and microbial respiration)

Net present value (NPV) the remaining value when the present value of the costs is deducted from the present value of the benefits

Net primary production (NPP) the annual increase in plant biomass, which is the GPP minus autotrophic (plant) respiration

Non-timber forest products (NTFP) any useful substance, material, or commodity obtained from the forest that is not timber. This would include game, furs, nuts, seeds, berries, mushrooms, oils, foliage, medicinal plants, resins, gums, fuelwood, and forage

NPK nitrogen, phosphorus, and potassium fertilizer

Old growth a particular stage of stand development, also called primary or virgin forest. The main canopy trees in old growth are dying, creating openings at different times as individual trees die, such that new age classes and cohorts are established and released to form an almost continuous all-aged multistructured forest. This perpetuation process is typical for the old-growth stage

One-cut shelterwood the practice where if the advance regeneration is already present and well established, presumably from de-facto past thinning operations or a natural disturbance event, then there is no reason to conduct a preparatory or establishment cutting; the removal of the **overstory** is all that is needed (synonym: overstory removal)

Organization measures of organization include the number of trophic levels of the food web and the number of interactions between trophic levels

Overstory the crown canopy of a forest or stand of trees

Overtopped in reference to the **Kraft Crown Class Classification** trees in this category have crowns entirely below the general level of the crown cover, receiving no direct light either from above or from the sides (synonym: **suppressed**)

Partial cut a general term that removes some proportion of basal area to the stand

Patches or patch-shaped stands denote the shape of the stand that promotes more uniform interior habitat as compared to edge habitat. Such shapes are circular or square as compared to narrow and long

Patch selection a selection regeneration method in which canopy trees of a sizable area (0.5–10 acres) are removed, creating a larger opening usually to encourage shade-intolerant tree species to establish (see **group selection**). The operation is conducted in different parts of the stand at periodic intervals (see **cutting cycle**)

Peeling a kind of girdling that can be effective on thin-barked trees. The bark must be "loose" meaning the tree must be growing (e.g., spring)

Periodic annual increment (PAI) the growth increment (usually measured as volume or diameter) of a tree or population of trees (stand) over a period of years divided by the number of years

Permanence a term that is used to define whether **additionality** of carbon has the long-term stability to remain sequestered through reforestation, protected through avoided deforestation, or increased through improved management practice

Permanent agroforestry agroforestry that continuously fights against competition and promotes the same plant composition over time

Phenological selectivity relates to the timing of plant growth in which application of herbicide will kill certain species that are actively growing but not species that are **dormant**

Phenotype the observable form and character of a tree or organism as a reflection of its **genotype** interacting with the environment

Phloem the thin layer of living cellular tissue surrounding the stem but beneath the bark and produced by the cambium, that is responsible for transporting the sugars produced by the leaves to other parts of the plant where they are stored or used

Photodormancy dormancy through light (e.g., germination is triggered by shifting seed from darkness to light)

Physical rotation where stands are cut at the time of culmination of **mean annual increment** (**MAI**) (synonym: biological rotation)

Physiochemical degradation degradation that affects the integrity of the soil fertility and hydrology. This is the most severe form of degradation as compared to **vegetative degradation**, given that the actual soil resource is affected, changing fertility and hydrology and, by implication, site productivity rather than vegetative, which affects the tree species composition and its structure

Pile and burn moving slash into piles that are constructed well in advance of the time when it becomes safe enough to burn, and then burning when there is no risk of the fire spreading

Pioneer vegetation early successional plant species that colonize open and disturbed areas; these species are usually short lived and reproduce prolifically

Pith the wood produced when the leader of the tree undergoes extension growth in that first-year stem (synonym: core wood)

Plantation a stand of trees that originated primarily by planting or direct seeding. Understory recruitment may occur through natural regeneration. Plantations may be single or mixed species and may be even aged or of multiple age classes

Poles and pole stage a size class of trees or a stage of an even-aged stand in which trees are greater than **saplings** but less than **young sawtimber**. In this book the pole size class has a range of approximately 1–6 in (2.5–15 cm) DBH

Pollard (pollarding) a coppice practice in which the main stem is cut above browse line of livestock to release multiple shoots from around the severed top

Post-establishment treatments refers to **intermediate cutting** and tending treatments that do not pertain to **regeneration methods** but to treatments made at other times of a **rotation**

Precommercial thinning **thinnings** that are carried out as investments for the future growth of a stand but the costs exceed any income from the cut

Pre-salvage cutting harvest cuttings designed to anticipate damage by removing highly vulnerable trees of commercial timber value

Prescribed burning a general term (also known as **controlled burning**) used to reduce hazards from wildfire, to prepare the site for **regeneration**, or to control vegetation as a **post-establishment treatment**

Primary growth tree growth from the growing tips (apical meristem) of the plant (e.g., shoot and root tips)

Production the amount deposited by growth whether or not it is harvestable within a stand. It is the integrated sum of the annual **net primary productivity** of a stand

Progeny test seeds from each parent tree are kept separate and sown in a replicated experiment

Progressive burning a **controlled burning** technique where parts of the stand area are burned separately and sequentially

Provenance the geographic source of seed or propagule

Pruning the removal of branches from a tree to improve the desired quality and form of the bole, fruit, nut and aesthetic (see **live**, **green**, **heading**, and **reduction pruning** methods)

***q*-factor** the relationship in a diameter distribution in which the number of trees in each diameter class is some multiple of that of the next larger diameter class. This relationship is thought to vary from 1.2 to 2.0. This is also called the BD*q* method, where B equals residual basal area, D equals maximum diameter in the stand, and *q* is the ratio factor. In a stand with a factor of 2.0, each diameter class would have twice as many trees as the next larger class

Rain garden sunken woody and herbaceous vegetation and soils designed to dissipate storm water off of roofing and small paved areas

Ray parenchyma bands of cells imbedded in the **xylem** whose chief function is storage of carbohydrates but they can act to impede infections from going around the stem

Recalcitrant seed that germinates almost immediately and shows no signs of dormancy

Reclamation restores soil and site productivity with new and novel assemblages of plants on severely degraded sites that have no original vegetation cover remaining

Reduced-impact logging (RIL) a mechanism to reduce carbon emissions by improving harvesting practices from business as usual through use of **best management practices**

Reduction cut the removal of a stem through pruning that is becoming codominant by shortening one of its lateral branches. This requires cutting back to a lateral branch that is at least one-third the diameter of the stem cut

Redundancy a form of resilience. An example is when multiple species have the same set of adaptations and mode of regeneration. If any one species in this group succumbs to a pathogen or insect, the remaining species perform the same functional and successional role within a stand's development

Reforestation new forest from the planting of trees or from naturally regenerated second growth on lands that had previously been forests

Regeneration the seedlings, saplings, and vegetative shoots that exist in a forest stand or the act of renewing a forest stand through either natural (seedlings, seed, or vegetative) or artificial (seeding or planting) regeneration methods (synonym: reproduction)

Rehabilitation restores ecological processes, species composition, and structure on the same trajectory as restoration (narrowly defined) but at a lower level as compared to the original ecosystem

Reineke stand density index an index based on inverse straight-line relationships between the logarithms of (1) average DBH, and (2) numbers of trees per acre. The index value is the number of trees for stands that have average DBH of 10 in (25 cm)

Relative density the number of trees per unit area as a percentage

Relay floristics the classic model of succession proposed by Clements whereby dominant species sequentially establish and then replace each other after a stand-replacing disturbance that eventually ends in a climax forest

Release disturbance disturbances that do not destroy or kill the residual vegetation at the **groundstory** (e.g., windthrow)

Release operations treatments designed to provide growing space for desirable tree **seedlings**, **saplings**, or **poles**, by removing competing vegetation (trees, shrubs, vines, herbaceous plants, or other seedlings and saplings)

Releve a method of vegetation classification that groups classes by presence and abundance of characteristic species that are neither ubiquitous nor rare (e.g., Braun–Blanquet method)

Removal cut (1) the final cut in either the **shelterwood** or **seed-tree regeneration method** that removes the remaining parent trees used to establish and shelter the new regenerating stand; (2) a kind of **pruning** in which the branch that remains is the dominant and the smaller is removed opposite to the **reduction cut**

Repeated cutting method a **release treatment** that relies on periodic **weeding** of competitive herbaceous growth that works by reducing the stored carbohydrates in the roots

Reserve trees trees that are purposefully arranged singly or in groups and left after **removal cutting** in **shelterwood** and **seed-tree regeneration methods** to provide an **irregular** diversity of age classes, species compositions, and structures above the regenerating portion of the stand

Resilience the stand's or forest's ability to maintain its structure and composition in the presence of a stressing agent or disturbance, either biotic (e.g., insect, disease) or abiotic (e.g., pollutants, wind, ice) or to rebound from it and to reorganize to create the same structure and composition (see **redundancy**)

Restoration a term that can be used narrowly as a literal interpretation of "restoring" to an original baseline condition, or it can be defined more broadly to include more refined words such as rehabilitation and reclamation

Restoration thinning a heavy **low thinning** applied to remove shade-tolerant conifers (e.g., white fir, Douglas-fir) from stands of overstory shade-

intolerant conifers, such as lodgepole pine and ponderosa pine where groundstory fire has been excluded for a period of time

Rhizome a modified stem that grows belowground, usually associated with ferns and grasses

Rime the coating of ice that can form when small droplets of water (e.g., fog) freezes on the cold surface of foliage and stems of vegetation

Riparian areas (zones) forest areas influenced and adjacent to bodies of water (e.g., ponds, streams, rivers)

Ripping very deep plowing often used to break subsurface hardpans

Root collar the juncture of the woody plant where the stem meets the roots. It is usually identified by a swelling or scar tissue in **hypogeal** seedlings where the cotyledons were attached (synonym: root crown)

Root pruning an expeditious substitute for transplanting in bare root nurseries to make the root systems shorter but more compact

Root sprouts shoots that grow from a **dormant** or **adventitious bud** on the roots (synonym: root suckers)

Rotation the interval of time between regeneration and harvesting the mature stand (see also **financial rotation** and **physical rotation**)

Roundwood unprocessed timber and pulp logs

Row thinning a type of **geometric thinning** in which every other row, or every third row is removed from a plantation

Rudimentary embryos when fruits are dispersed, seeds are immature and need time before the seeds mature and germinate

Salvage cutting harvest cuttings done to save commercial timber in dead or damaged trees

Sanitation cuttings cutting treatments designed to eliminate trees that have been attacked, or appear in imminent danger of attack, by dangerous insects and fungi in order to prevent them from spreading to other trees

Saplings and sapling stage a size class of trees or a stage of an even-aged stand in which trees are greater than **seedlings** but less than **poles**. In this book, the size class ranges between trees greater than breast high (4.5 ft/1.4 m) in height and approximately 1 in (2.5 cm) DBH

Sapwood the zone of younger **xylem** wood that is functional, transporting water

Sawtimber and sawtimber stage a size class of tree or a stage of an even-aged stand in which trees are greater than approximately 10 in (25 cm) DBH

Scaffold branches development of a tree and branch structure in fruit and nut trees that will set the frame of the tree that will allow regular shoot pruning (e.g., **bench cuts**) to promote flowers

Scalping a site preparation treatment that takes the top off the soil exposing the mineral soil beneath in patches to eradicate vegetation around the planted seedling

Scarification (1) any site-preparation treatment that exposes the mineral soil; (2) a seed-preparation treatment to break internal dormancy by making the seed coat permeable and exposing seed to a water wash, acids, and/or heat

Scion a cut stem used in grafting (see **grafting**)

Secondary growth zone of growth that increases the thickness of the woody stems by the division of the **cambium** meristem cells that produce new tissues inward (especially **xylem**)

Second-growth forests that regenerate after a human-caused disturbance, usually clearance for agriculture and subsequent abandonment or after heavy logging

Seedlings or seedling stage a size class of tree or a stage of an even-aged stand whereby regeneration of seed origin is less than the size of a **sapling**. In this book, the size class includes all individuals less than breast high (4.5 ft/1.4 m).

Seedling sprouts vegetative sprouts that come from the root collar of small seedlings and saplings

Seed orchard an intensively managed plantation of specifically arranged trees for the mass production of genetically improved seeds to create plants, or seeds for the establishment of new forests

Seed-production area stands can be thinned to leave only those trees with good phenotypes, thus increasing the probability that seed collected in the stand will be from parents of good genetic stock

Seed-tree regeneration method a harvest that is carried out to remove most of the trees in a mature stand, leaving a small number of residual trees (called **seed trees**) to produce the seed for regenerating a succeeding stand. Site treatments associated with seed-tree methods are lethal to the groundstory to ensure germination and establishment of shade-intolerant regeneration

Seed trees trees that are purposefully left as a source of seed in the seed-tree regeneration method

Seed tree with reserves the **seed-tree method** in which **reserve trees** have been left after regeneration establishment in order to maintain a long-term two- to three-aged forest structure

Seeps the emergence of subsurface soil water on the soil surface

Selection regeneration method the component of the **selection system** to regenerate such stands. Selection is the only **natural regeneration method** that is not defined by the focus of the nature and origin of its regeneration. The method is defined by age-class distribution. The selection regeneration method attempts to create an **all-aged** (four or more age

classes; sometimes three) that is **balanced** in age-class distribution (meaning that an equal area is apportioned to each age-class within the stand)

Selection system applies to silvicultural programs that are used to maintain **balanced all-aged** (**uneven-aged**) stands. Selection systems contains at least three, but usually more, well-defined age classes, where "well-defined" means differing in total height and age, not just in stem diameter

Selective cutting **partial cutting** that removes only the largest and most valuable timber trees

Self-pruning branches that die from lack of light, as a result of shading by branches of adjacent trees. It is a reflection of **self-thinning** within the individual tree (synonym: natural pruning)

Self-thinning and the self-thinning law the mortality caused by competition between individual trees for growing space. The law is the relationship between the maximum number of individuals that can occupy a site and the average size of the individuals. In studies, the maximum number of plants of any given size that can exist on a site is correlated to the average biomass raised to the 3/2 power

Serotiny fruits or cones that remain on the tree for long periods of time until fire or desiccating heat opens the fruits or cones, dispersing the seeds

Shade tree/crop combinations two-storied agroforestry systems with one or more species of taller trees growing above an herbaceous, shrub, or small tree crop

Shearing a pruning technique for shrubs that removes all the outer shoots of the crown efficiently, such as in hedges

Shelterbelt a strip of trees and/or shrubs used in agricultural or urban settings to reduce windspeed

Shelterwood regeneration method establishes new **even-aged** regeneration by gradually opening the canopy of a mature stand, using a series of partial cuttings. These harvests gradually reduce the canopy density of the mature stand. This method is used to promote the establishment of tree species that are mid-tolerant to very tolerant of shade, relative to their competitors in mixed stands that are shade-intolerant **pioneers** that often dominate **stand initiation** and **stem exclusion**. The method provides only moderate light in the early stages of the regeneration cut. Later cuts will open the overstory to provide greater light for more rapid height growth and finally remove the canopy in the **removal cut**

Shelterwood with reserves a shelterwood in which individual or groups of trees have been left to form two or three age classes (**multi-aged**) after the regenerating cohort has established and the removal cut completed

Side grafts a graft where the much smaller **scion** is inserted into the side of the stem of the larger **stock**

Silvicultural system a planned program of silvicultural treatments extending throughout the life of a stand

Silvopastoral systems an agroforestry system that integrates woody plants (trees) with pasture for livestock

Simple coppice method of regeneration all standing trees are cut at the end of each rotation, and an even-aged stand springs up almost immediately from sprouts

Single-aged synonym: **even-aged**. For the purposes of this book, single cohort and single-aged are defined as the same as one effective age class (see definitions of **cohort**, **chronological age**, and **effective age** for clarification)

Single-tree selection method a **selection regeneration method** focused on creating canopy openings by removing individual mature trees to secure new regeneration in small gaps

Site classification the method of spatially delineating differences in site productivity. This can be done directly by measuring differences in soil fertility or indirectly by observing the presence and absence of indicator plant species of different soil fertilities

Site index a measure of site productivity for a given tree species by measuring the average height of the **dominant** trees of an even-aged aggregation of trees at some index age

Site preparation **site treatments** applied to **slash**, groundstory vegetation, forest floor, and soil in order to make the site suitable for natural or planted regeneration and to exclude or reduce competing vegetation. Most of the preparation treatments are applied during establishment, but some are started well in advance of harvest cutting or applied throughout the **rotation**

Site treatments groundstory treatments to encourage the desired regeneration and revegetation. They include three main categories: (1) preparation; (2) protection; and (3) improvement, conversion or restoration

Skidders machines that drag the logs to the landing from the harvest site. This can include machines called rubber-tired skidders, tractors, elephants, horses, oxen

Skidding and skid trails a method of log transportation from the site of cutting to the landing by dragging. The trail created and/or used to drag the log is the skid trail

Slash logging debris left from cutting treatments and timber harvests

Snags standing dead trees

Soft mast berries and other fleshy fruits produced by species such as cherry

Soil organic carbon (SOC) carbon tied to organic matter within the mineral soil

Solid wood products sawtimber. There are two broad categories of sawn timber: construction or furniture and trim

Somatic embryogenesis cloning a plant that originates from a single or group of cells that are from the vegetative portions of the donor plant

Source areas areas within the stand where soils are so saturated that water can flow from them beneath, or even on top of, the soil surface as **seeps** and springs

Spot burning burning concentrations of slash within the stand and not the whole area (synonym: patch burning)

Stand the basic management unit for the application of silvicultural decisions and treatments; they are therefore the basic unit of land use planning in forests. Stands are defined by differences in age, composition, stocking, and site productivity

Standard reserve trees usually of seedling origin within coppice-origin stands (see **coppice-with-standards**)

Stand density a quantitative measure of stocking expressed as the number of trees per unit area

Stand density index (SDI) thinning guidelines that directly relate tree size to stand density. See **Reineke SDI** or **stand density management diagrams**

Stand density management diagrams a set of diagrams created to graphically illustrate measures of tree density and tree size over developmental time for a particular species

Stand dynamics the study of changes in forest stand structure over time, including stand behavior after disturbances

Stand initiation the first stage in stand development after a disturbance has created vacant growing space, the new trees that have become established in it (or preexisting larger ones that expand into it) do not fully occupy the space. Until they do, there is opportunity for additional plants to fill the empty spaces. Often, the plants that fill the newly vacant spaces are herbaceous annuals or other short-lived species that may come and go quickly

Stand prescription a planned series of silvicultural treatments to meet management goals

Stem exclusion the second stage of stand development in which the trees start to compete with each other; the more vigorous ones encroach into the growing space of weaker trees that eventually die, usually from lack of light or soil moisture. Establishment of additional regeneration of tree species is also prevented

Stem injection a method of applying herbicide to trees in **release treatments** (e.g., **liberation**) or for **timber stand improvement** (**TSI**)

Stock the root and stem used to unite with another stem, called the **scion** (see **grafting**)

Stocking a measure of growing-space occupancy as compared to a pre-established standard. Common measures of stocking are based on basal area, stand density index, and crown competition factor

Stocking diagrams diagrams built upon the statistical relationships between the diameters and the numbers per acre (hectare) of trees for hypothetical stands that consist of open-grown trees of uniform stem sizes that have just barely closed. The upper limit beyond which stand density should not be allowed to increase, is defined by similar relationships between numbers and sizes of trees in fully stocked stands

Stool shoots usually crooked and slow-growing, develop from stumps that have been cut so often over so many decades that they have callused over with injury tissue originating from the cambium and bark. Such stumps or **stools** may have spread to be several feet (1 m) in diameter, and resemble the mysterious burls that sometimes form on tree stems. Most of the sprouts arise from **adventitious buds**, and only some are from released **dormant buds**

Stratification (1) the vertical differentiation of crowns and heights of trees over time and space; (2) conditions created by storing the seed in cool, moist substances, just as would occur in the natural forest floor

Stratified canopies well-differentiated crowns of tree species and individuals growing at different rates and/or of different ages

String tree structure a pruning program to select for dominant leaders and well-spaced smaller branches in newly planted street and shade trees to reduce future branch breakage when trees are mature

Strip or spot seeding direct seeding in strips and spots

Strip selection a **selection regeneration method** in which the arrangement of cuttings consists of repeating strips that are discreetly separated to represent all ages across the stand

Strip shelterwood follows the same protocols as the **uniform shelterwood**, but the arrangement of each of the operations consists of repeating strips that are discreetly separated

Strip thinning a type of **geometric thinning** that consists of cutting or crushing trees in parallel strips through a stand. It is often applied **precommercially** to thick naturally regenerated stands that have stagnated

Stump sprouts sprouts that arise from **dormant buds** at the root collars of tree stumps. These shoots almost invariably develop from **lateral buds** that were originally formed on the leading shoot of the seedling

Sub-lethal disturbances that variably kill all forms of vegetation on a site and that physically disturb the soil. Some areas are less impacted than other areas

Successional agroforestry agroforestry that allows competition to occur and progress in changing plant composition

Suppressed in reference to the **Kraft Crown Class Classification**, trees with crowns entirely below the general level of the crown cover, receiving no direct light either from above or from the sides (synonym: **overtopped**)

Swidden agriculture the practice of agriculture after forest clearance that has worked the area for a number of years before being abandoned, either because of the vigor of regrowth or loss of soil fertility or a combination (synonym: shifting agriculture)

Taungya the practice of incorporating arable crops at the time of plantation establishment for a number of years before the crops are shaded out by canopy closure

Tetrazolium test a germination test that stains all viable seed red as a measure of respiration and therefore viability

Thermodormancy dormancy through temperature change (simulating winter by chilling)

Thinning the judicious removal of trees to reallocate growing space to other trees and plants. Thinnings are made to individual trees and stands that are considered beyond the release stage of treatment (i.e., beyond **seedlings**, **saplings**, and **pole-stage** stands). It is a **post-establishment treatment** done to remove individual trees or groups of trees to create new growing space, with the main purpose of producing larger trees for timber production or for sap or latex production from the stems. Thinning can also be used for producing stand structures that create viewsheds, increased water availability, forest health, or fire protection

Thinning cuts a kind of **pruning** in shrubs that remove the entire shoot back to its base

Timber stand improvement (TSI) the removal of less desirable trees in order to improve composition and quality of the residual stand

Tissue culture producing whole new plants from culturing small fragments of tissue in media that supply the complex biochemical substances needed for plant development

Tongue grafts a kind of **grafting** in which the **scion** and **stock** are of the same size, with the scion placed on top of the stock stem (synonym: whip)

Tracheids conducting tubes in the **xylem** of gymnosperms

Transplanting a term used when seedlings are lifted from the soil or from pots and moved to a wider spacing or larger pots in a nursery to encourage greater growth

Tree gardens multipurpose mixed plantings of trees and shrubs that are all-aged or multiple-aged and continuously changing

Unbalanced two, but usually three or more age classes that are not equally represented in area within a stand

Unbalanced all-aged stands where four or more age classes are unequally distributed (see **selection regeneration method**)

Unbalanced multi-aged where there can be two to three age classes with the most recent regenerating age class dominating the number and spatial area of the stand. This age class is associated with **irregular seed-tree** or **shelterwood systems**

Underplanting a form of enrichment planting beneath a more mature forest canopy

Understory reinitiation the third stage of stand development where scattered trees that have previously been successful in competition with other trees begin to be lost to pests, other damaging agencies, or cutting operations, and their crowns do not fully close again. The small vacancies thus created allow the establishment of new plants beneath the old stands. This is often advance regeneration of shade-tolerant species

Uneven-aged a broad term denoting **stands** that can be **multi-aged** or **all-aged** and that can be **balanced** or **unbalanced** in age-class distribution

Uniform shelterwood a shelterwood whereby the pattern of operations is sequentially applied equally and uniformly across the stand, unlike **strip** and **group shelterwoods**

Variable-density thinning a thinning used to promote a greater variety of ecological conditions than would normally be found in a uniformly spaced stand. It is designed to foster an increase in biodiversity in the stand. Thus, variable-density thinning can be conceived to be almost equal and opposite to **free-form thinning**

Variety synonym for subspecies

Vegetation management (or vegetation control) a general **release operation** commonly used to refer collectively to both **cleaning** and **weeding**. These treatments can be used to release seedlings of any desirable species, for timber production, forest restoration, or other purposes

Vegetative propagation by **cuttings**, **layering** or other asexual means

Vegetative degradation a type of degradation that affects the forest structure, composition, and development. Vegetative degradation includes those impacts that alter tree species composition and stature in a way that does not allow the composition and structure to come back

Vessels conducting tubes in the **xylem** of angiosperms

Volume method of regulation a form of forest management regulation in which the estimated standing volume of merchantable timber in the forest is used to determine the allowable annual or periodic

harvest. Considerations include the volume of wood, the rate of growth, both current and potential, and the volume of growing stock, both existing and desired

Watershed an area of land where all inputs (rainfall, particulates, weathered nutrients) ultimately drain to the same point through the flow of water

Weeding **release operations** designed to remove all plant competition that may be growing above, beside, or below the crowns of all the young desirable trees

Wildlings natural regeneration (often advance regeneration) that is dug up and replanted either in a nursery or directly back on another site for reforestation purposes

Wind firmness tree stability in wind

Wood fiber products dissolving wood into fibers such as pulp for paper manufacture

Wood pastures when trees are routinely **pollarded** at about 6 ft (~2 m) or more, such that **dormant buds** are released at the top of the bole to produce sprouts; the young regrowth is inaccessible to browsing animals. This can be a very successful technique for integrating pasture and livestock into woodlands that are managed for firewood, fodder, and other sprout-dependent products

Wrenching root pruning bare-root seedlings at time of planting when the roots are too long for the planting hole

Xylem cells of various kinds (e.g., vessels, parenchyma) layered inward annually by the **cambium** and comprising the wood that is responsible for transporting the vast amount of water to the leaves

Yarding a method of harvesting timber by cable to the log landing

Yield the amount that is actually harvested or could be harvested from a forest stand

Young sawtimber and young sawtimber stage a size class of tree or a stage of an even-aged stand in which trees are greater than **poles** and less than **sawtimber**. In this book, the size class is defined as greater than 6 in (15 cm) DBH and less than 10 in (25 cm) DBH

Zero-margin selective cutting a cutting that removes all trees that can be utilized without financial loss

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